INVESTIGATION OF ASTM E 238 BEARING PIN PROPERTIES FOR VARIOUS AEROSPACE ALLOYS

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ABSTRACT

Investigation of ASTM E 238 Bearing Pin Properties for Various Aerospace Alloys

Trevor J Lee

Aircraft are often designed with numbers determined by testing in a lab, rather than by repeatedly building prototypes. These lab tests conform to testing specifications so that the numbers can be compared between manufacturers, suppliers, and lab technicians. One such specification is ASTM specification E238 – 84(08), and it is used to determine important properties of a bearing pin joint like hinges, bolt holes, and rivet joints. The properties determined from this fastener-through-plate method are bearing strength, bearing yield strength, and bearing stiffness.

Adhering to the methods outlined in ASTM E238, a study was performed, looking at the effects that plate material, fastener used, fastener lubrication, and plate hole preparation method (whether drilled and reamed or just drilled) have on the three bearing joint properties. The plate materials used were Al 7050 – T7451, Ti – 6Al – 4V (mill annealed), and PH13 – 8Mo – H1000. The fasteners were Ti – 6Al – 4V screws, coated A286 screws, and high speed steel (HSS) pins used as a control. Lubrication was tested using a corrosion inhibitor, PR – 1776M B – 2 from PRC – DeSoto, on the fastener or leaving the fastener uncoated. The HSS pins were always tested in the uncoated condition. 54 runs were performed, as outlined by a D-optimal design of experiment.

It was discovered from the statistical analysis of the results via ANOVA that both the plate material used and the pin material, whether a screw or a pin, had a significant effect on the bearing strength, bearing yield strength, and bearing stiffness. The interaction between the two factors was also significant on all responses but the bearing stiffness. PH13 – 8Mo – H1000 plates seemed to perform best on average, followed by Ti – 6Al – 4V plates, then Al 7050 – T7451 plates. PH13 – 8Mo – H1000 and Ti – 6Al – 4V plates had similar bearing strength and bearing yield strength averages with the HSS control pins being used, which had the highest mean values for a given plate and fastener. The Ti – 6Al – 4V and A286 screws behaved and performed statistically similar in most cases, except when hole preparation method was take into account. The Ti – 6Al – 4V screws performed better when the hole was drilled and reamed, while the coated A286 screws performed better when the hole was drilled only. All screws had lower resulting bearing properties than the HSS control pins.

It was also found that ASTM specification E238 – 84(08) is a precise test method, since the method could be performed repeatably and reliably with no missing data points. Therefore, this ASTM testing method is reasonable for determining bearing properties, which can then be used to design aircraft.

Key Words: ASTM E238 – 84(08); Bearing Strength; Bearing Stiffness; Aluminum 7050 – T7451; Ti – 6Al – 4V; PH13 – 8Mo; A286; High Speed Steel

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INTRODUCTION

Given the complexity of modern aircraft, many material and component specifications are used in their design. Specifications are standardized methods for determining the performance of materials or components. Since specifications are standardized and widely adopted, they allow for direct comparison not only between materials and components, but also between different testing groups or companies. This permits the results to be used by all interested parties without using confusing or misleading jargon or results. In the case of structural materials and components, the specifications usually describe one or a few of the many possible stress states (tension, shear, or torsion, for example), and then call for these stress states to be applied to a specific material, component, or combination of components.

One example of a group of components to simulate in design is a plate with an inserted, unrestricted fastener, oriented normally to the plane of the plate. This combination can be seen in various places in an aircraft, such as the bolt holes in landing gear or the pivot joints used to attach the flight control surfaces (ailerons or elevators) to the wings. In both cases, the accurate simulation of performance is mandatory, given their critical need in the operation of the aircraft and great expense of real-world testing of these components.

In order to determine the performance of such joints in a lab setting, ASTM specification E238 – 84(08) is used, which is designed to evaluate the response of the plate, fastener, and hole to stress. In addition to bolt holes for landing gear, this specification is also used for the simulation of riveted structures (Caputo, 2008). The test establishes a value for the bearing stiffness, bearing yield strength, and bearing strength for the joint. The bearing stiffness is the linear proportionality between bearing stress and bearing strain (where a linear relationship exists), and the bearing strength is the amount of bearing stress that the test specimen can support before fracture. Bearing yield strength is the amount of stress endured where the bearing displacement deviates from linear behavior by a significant amount (2% of the plate hole diameter). These properties are then compared to simulated loads on the components of the aircraft. It can then be decided if the performance of the simulated joint is sufficient for use on the aircraft, by comparing the stresses of the aircraft to the properties of the simulated joint.

ASTM specification E238 – 84(08) is performed by loading a fastener-and-plate assembly into specialized fixturing. The fastener is then loaded in shear in close proximity to where it enters the plate, on one side. The layout and applied load are shown in Figure 1. From the data collected, the properties listed above can be determined, and then utilized to evaluate performance of an actual joint defined by the parameters used for testing.

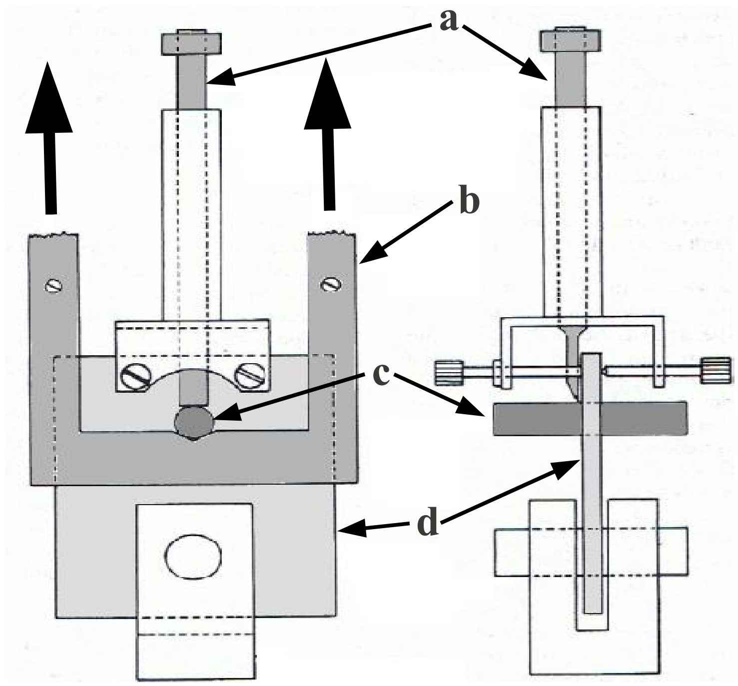


Figure 1: Side view (left) and front view (right) of the fixturing and specimen used in ASTM E238. Shown are the plunger used to measure the displacement (a), the frame used to apply the load in tension (b), the bearing pin to which the load is applied (c), and the plate specimen (d). Strain rate is applied on the loading frame in the direction shown. (ASTM E238, 2008)

For any specification to be accepted and used, it must be possible for the user to determine if the test results are valid or erroneous, as well as be able to yield reproducible testing results. Since the equipment in this study wasn't calibrated, determining validity was not possible. However, precision could be verified simply by observing the scatter of the data. This precision is important, since imprecise results will appear to be random, and will thus require more testing, and thus resources, until the results can become more precise. Many different factors can affect the precision of this specification. Some examples include variation in the materials used, like the specifics of the various heat treatments (temperatures, times, and cooling methods), plate thickness preparation method (forging it to the proper thickness versus machining it), and variations in the geometry, like the fastener-hole clearance. Even the method of cleaning can have an effect on the results; it has been found that oils from human contact tend to lower the apparent strengths and stiffness results from the test (Stickley, 1962). In another standard governing the determination of bearing properties, those oils were found to lower the bearing strength by 10 percent when tested without sufficient cleaning (MMPDS, 2012).

In the interest of determining if ASTM specification E238 is sufficient to precisely evaluate the performance of a fastener-and-plate joint, many factors have to be controlled in order to determine if the testing factors have any significant effect on the results. For example, the dimensions of the specimens and the method of cleaning are typically kept constant in order improve testing precision. Since the properties of the various materials could be altered by the manipulation of the materials, the heat treatments were also verified for each material to ensure that all samples of the same materials were subjected to the same heat treatment. Once these factors were identified and controlled, factors of greater interest could be studied. The factors identified for this purpose were the plate and fastener materials to be used, if a fastener corrosion inhibitor was used or not, and the method for preparing the hole in the plate, since the method, whether simply drilled or drilled and reamed (as is standard practice), can affect the amount of cold work around the hole, and thus alter the results (ASTM E238, 2008). The materials to be studied were common aerospace alloys subjected to heat treatments typical of plate components: aluminum 7050 – T7451, Ti – 6Al – 4V in the mill annealed condition, and PH13 – 8Mo in the H1000 condition. For the fasteners, the materials to be utilized were Ti – 6Al – 4V screws, coated A286 stainless steel screws, and a high-speed steel (HSS) pin used as a control.

Once these parameters were chosen, the following research questions could be answered:

> Can the effects of the plate material (Al 7050 – T7451, Ti – 6Al – 4V (mill annealed), and PH13 – 8Mo – H1000), the fastener used (Ti – 6Al – 4V screws, coated A286 screws, or HSS pins), lubrication, and cold work (due to hole preparation method) on bearing mechanical properties be measured precisely by following ASTM E 238 – 84 (08)? Are there any observable trends in the data?

EXPERIMENTAL PROCEDURES

Sample Verification

To verify that the samples were fit for testing and thus would yield repeatable results, each plate specimen was measured 5 times in the dimensions shown in Figure 2.

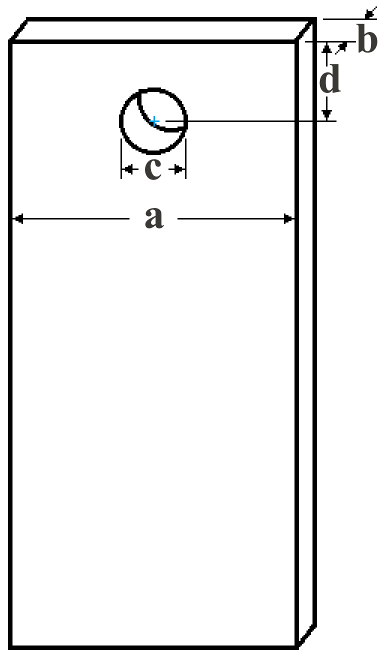


Figure 2: Dimensions measured for each plate specimen. Shown are the width (a), thickness (b), hole diameter (c), and the edge distance (d).

The results from these measurements are shown in Table I.

Table I: Average Dimensions of Each Plate Specimen, Standard Deviation Shown in Parentheses

Material	Width	Thickness	Hole Diameter	Edge Distance
Al 7050 – T7451	1.4974 (.0066)	.1240 (.0005)	.2497 (.0004)	.5026 (.0067)
Ti – 6Al – 4V (mill annealed)	1.5001 (.0014)	.1175 (.0034)	.2499 (.0009)	.5010 (.0024)
PH13 – 8Mo – H1000	1.4980 (.0043)	.0891 (.0012)	.2501 (.0006)	.5019 (.0016)

As shown, the standard deviations are low relative to the average values, so the qualifying measurement data is seen as reliable, leading to repeatable results from the bearing tests that follow. The largest deviations are in the edge distance ratios; this is most likely due to the measurement error resulting from measuring the distance from the curved surface of the hole to the flat surface at the edge of the plate. The deviations in the specimen widths are also larger than those of the diameter or the thickness, but since the width is a significantly larger dimension, this is to be expected.

Once the dimensions were verified for each sample, the heat treatments for each material was verified. This was done by randomly selecting 3 of the samples of each material. These samples were used to verify the heat treatment via Rockwell hardness. The proper scale and target value for each material type tested for the plate specimens, as well as the actual values for each sample, is shown in Table II.

Table II: Target Hardness and Actual Hardness Values for Plate Specimen Materials, St Dev in Parentheses

Material	Target Hardness	Actual Hardness
Al 7050 – T7451	82 HRB (min)	109.122 (1.067)
Ti – 6Al – 4V (mill annealed)	35 HRC (min)	32.880 (.192)
PH13 – 8Mo – H1000	43 HRC (min)	35.200 (.200)

As shown, the Al 7050 – T7451 specimens exceeded the specified values, while the Ti – 6Al – 4V and PH13 – 8Mo – H1000 plate specimens fell short of the specified value. This could lead to an observed bearing strength and bearing yield strength for the Ti – 6Al – 4V and PH13 – 8Mo – H1000 plate specimens lower than other Ti – 6Al – 4V (mill annealed) or PH13 – 8Mo – H1000 plate specimens. However, since no values exist in literature to compare to compare to these strengths, this is not seen to be of significant concern. Also, the scatter in the Al 7050 – T7451 is significantly larger because the values are at the upper extreme of the Rockwell B scale; accuracy decreases at the extremes of the scale (HRB 110 is considered the maximum value).

The fastener specimens were then verified by macrohardness. The target values for each, as well as the actual results, are shown in Table III. The macrohardness was measured by a Rockwell C hardness tester, on 3 of each fastener material, again selected randomly. All three measurements were made on the end or head of the fastener. Since the heads of the screws were large compared to the diameter of the screw, significant scatter was introduced into the hardness data for these fasteners from the deflection of the head, as shown in Table III.

Table III: Target Hardness and Actual Hardness Values for Fastener Materials, St Dev in Parentheses

Material	Target Hardness	Actual Hardness
Ti – 6Al – 4V	60-64 HRC	32.660 (6.119)
A286		32.780 (7.022)
HSS		64.580 (.466)

As shown in Table III, The HSS pin exceed the ASTM E238 – 84(08) specified range. Alternatively, the two screw fasteners were insufficiently hard. However, this was deemed as acceptable; since the purpose of ASTM E 238 – 84 (08) testing is to simulate real-world scenarios, utilizing fasteners that don't meet the requirements of the specification can still yield meaningful results. The requirement outlined by the specification is meant to remove the fastener as a variable; if it is intentionally being observed, then a fastener with lower hardness can provide valuable information about the fastener being tested.

The final qualification for the specimens was to measure each fastener to ensure it wasn't bent; each fastener was placed between two centers (for screws) or on V-blocks (for pins), and a pin gauge was used in a moveable fixture on top of a microflat to ensure consistency. The gauge was then placed up against the fastener, and the displacement relative to the left-hand edge was measured. An example of the setup used for the HSS pins is shown in Figure 3.

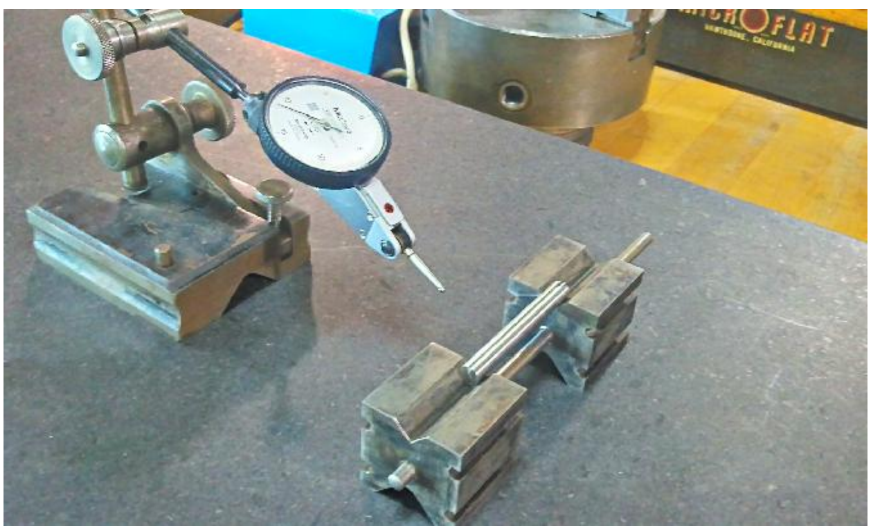


Figure 3: V-block and pin gauge setup used for qualifying the HSS pins. The Ti – 6Al – 4V and coated A286 screws used the same pin gauge setup for measurement, but used centers to suspend the screw.

The screws were measured in two places at 120° intervals, for a total of 6 measurements. Alternatively, the HSS pins were measured three times, for a total of 9 measurements (since the HSS pins were used as a control, straightness was more critical). The measured deviations from all fastener specimens were consolidated, and are shown in Table IV.

Table IV: Pin Straightness Measurements, St Dev in Parentheses

<table>
<tr><th>Material</th><th>Measurement 1 (mil)</th><th>Measurement 2 (mil)</th><th>Measurement 3 (mil)</th></tr>
<tr><td>HSS</td><td rowspan="3">0.000 (.000)</td><td>-0.025 (.324)</td><td>-0.250 (.446)</td></tr>
<tr><td>A286</td><td>-0.092(.446)</td><td></td></tr>
<tr><td>Ti – 6Al – 4V</td><td>0.017 (.664)</td><td></td></tr>
</table>

Since the greatest amount of variation, that between measurements 1 and 3 for the HSS pins, was around 0.25 mil (0.00025”), the pins deviated only slightly from straight.

Once all qualifying data was collected, the data were compared against the relevant specification, ASTM E238 – 84(08) for the dimensions and macrohardness of the fasteners, SAE standard AMS 2658B for the hardness of the Al 7050 – T7451 plates, the Aerospace Structural Metals Handbook (Code 3707) for the hardness of the Ti – 6Al – 4V plates, and SAE standard AMS 5629E for the hardness of the PH13 – 8Mo – H1000 plates. The values for the hardness of the Ti – 6Al – 4V are not generally used as an acceptance criterion (Aerospace Structural Metals Handbook Code 3707, 2006). Therefore, the deviations from the specified values are not necessarily indicative of a failed heat treatment.

From this, it was found that the Ti – 6Al – 4V plates, Ti – 6Al – 4V screws, and coated A286 screws failed to comply with the specifications, while all other samples met or exceeded those specifications.

Bearing Sample Coating and Cleaning

All fastener specimens to be coated were randomized and coated in a fume hood. The coating, the corrosion inhibitor PR – 1776M B – 2 from PRC – DeSoto, was applied by rolling the fastener in a nitrile glove that had the corrosion inhibitor on it, therefore applying the coating only to the surface without coating the head of the fastener. The pins were then allowed to dry undisturbed for at least 24 hours prior to testing.

Nitrile gloves were worn for the duration of the testing. Just prior to testing, the plate specimen being used was cleaned with a paper towel and acetone. The run order was randomized, and the fastener being tested was inserted into the plate.

Testing Conditions

After each specimen was prepared, the test was carried out according to ASTM E238 – 84(08). The test was performed using a crosshead rate of 0.25 in/min, making a strain rate of 0.05/min (based on 5 inch-long samples). Unlike in the specification, the lower clevis was not used, since the clevis pin hole for the samples did not permit the bottom of the sample from clearing the inside of the lower clevis. Instead, a typical grip was used, tightened around the base of the plate specimen being tested. The highest point gripped on the specimen was a distance of 1.5” from the bottom edge of the plate; this is the nominal furthest point that the clevis pin hole is from the bottom of the plate specimen. The plate was fully aligned to the left inside the grip to ensure repeatability. Also, since there was no extensometer readily available that was compatible with the plunger and plunger guide, they were not used, and instead the crosshead displacement was used to approximate the extension of the sample.

Taking these variations into account, the specimen and fixturing were assembled, as shown in Figure 4.

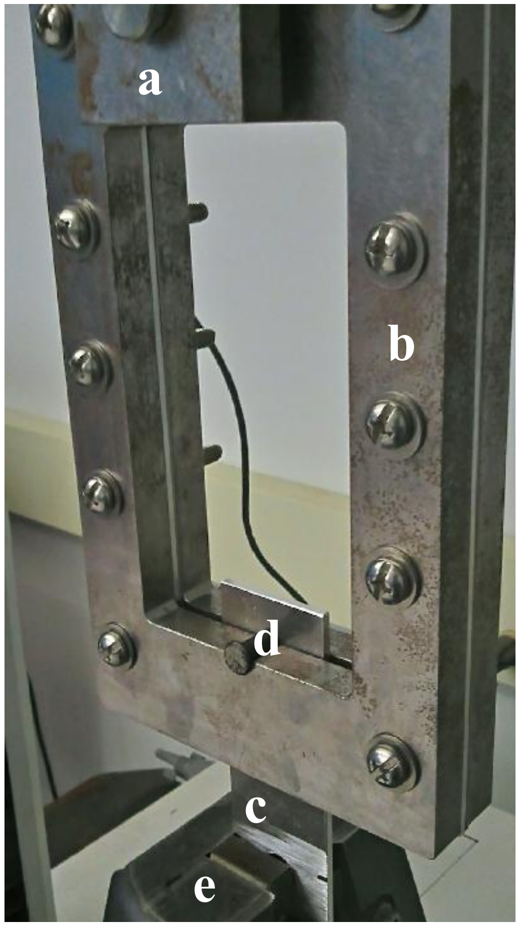


Figure 4: Assembled testing setup. Shown is the upper clevis (a), loading frames (b), plate being tested (c), fastener being tested (d), and lower grip (f).

Data Evaluation

The properties were then determined, as per the specification. Bearing strength and bearing stiffness were determined using a method analogous to tensile strength and modulus in uniaxial tension tests. The bearing strength measured was the maximum stress supported during the test. The bearing stiffness was the linear proportionality coefficient (slope) in the elastic region of the stress-strain curve; this is developed by transforming the load-extension curve. The stress is determined by dividing the load at each point by the bearing area, defined as the product of the plate hole diameter and the specimen thickness. The strain is calculated by dividing the displacement by the plate fastener hole diameter (ASTM E238, 2008).

In the case of the bearing yield strength, a specific method, as shown in Figure 5, was utilized. This method defines the bearing yield strength as the stress corresponding to the first point upon loading the sample where the difference in extension between the linear proportionality estimate and the actual sample extension exceeds 2% of the diameter of the hole in the plate, unlike the typical 0.2% extension used in uniaxial tension testing.

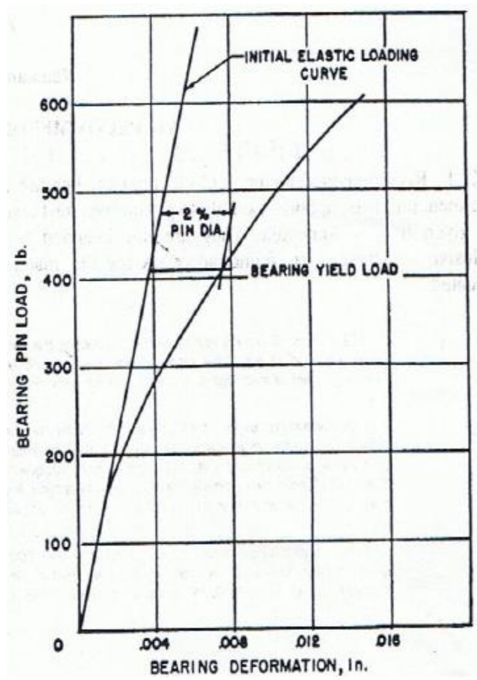


Figure 5: Example of how to determine bearing yield strength. Material used is AZ31A-H24 sheet at room temperature. (ASTM E238, 2008)

In order to determine the bearing strength, bearing stiffness, and bearing yield strength, the load-extension curve was used for each sample. The greatest load achieved by the test was the ultimate tensile load, which was divided by the bearing area to determine the bearing strength of the sample. Next, two different loads were chosen that corresponded to two extensions withing the elastic region of the curve. These loads and extensions were then used to determine the bearing stiffness by the equation

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} = \frac{\frac{P_2 - P_1}{A}}{\frac{L_2 - L_1}{D}}$$

where P is the load selected, A is the bearing area, L is the corresponding extension, and D is the plate fastener hole diameter.

To determine the bearing yield strength, the linear proportionality line was offset to the right (towards longer extensions) a distance of 2% of the plate fastener hole diameter, or 0.005”. If the load-extension curve intersected the yield offset line prior to failure, then the yield load was equal to the load that corresponds to the intersection. If not, then the material did not yield, and the yield load is equal to the ultimate tensile load. The yield load was then divided by the bearing area, as with the ultimate tensile load, to determine the yield strength of the specimen.

An example of the graphical determination of the loads and displacements that were used to determine stresses and strains, respectively, is shown in Figure 6.

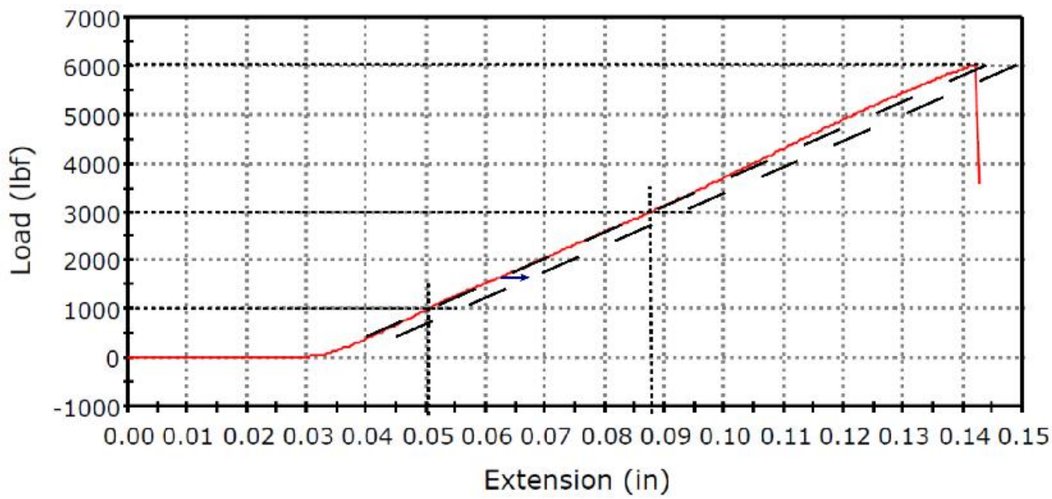


Figure 6: Typical load-extension curve. Properties determined from this curve are the ultimate tensile load (a), upper and lower stiffness loads (b, arbitrarily chosen), and upper and lower stiffness extensions (c). Also shown are the linear proportionality lines and the yield offset. Since the curve doesn't intersect the offset yield line, no yielding occurred.

This process was used for all samples, then the bearing strength, bearing yield strength, and bearing stiffness were used for analysis of the factors.

RESULTS

Design of Experiment

For this experiment, a total of three levels of plate material (Al 7050 – T7451, Ti – 6Al – 4V (mill annealed), and PH13 – 8Mo – H1000), three levels of pin material (Ti – 6Al – 4V, coated A286, and HSS pins), two levels of fastener hole preparation method (drilled only and drilled & reamed), and two levels of fastener lubrication (lubricated and not lubricated) were used. This results in a total of 36 possible combinations (a full factorial design would have 36 runs in it). However, 18 aluminum plates, 20 Ti – 6Al – 4V plates, and 19 PH13 – 8Mo – H1000 plates were supplied for the project.

An Analysis of Variance (ANOVA) approach would be used to determine the likelihood of an effect or interaction being statistically significant with 95% confidence (significance level, $\alpha = 0.05$). This confidence level provides a good balance between a higher chance of type I error (failing to detect a true effect) at lower significance levels, and a higher chance of type II error (detecting a false effect) at higher significance levels. The upper bound for type II error is equal to the significance level times the number of factors, which is 4 main effects + all 6 two-way interactions = 10, for a upper bound of 50%, which is somewhat high. As a preliminary screening study, it is thought to be better practice to determine a greater-than actual number of significant factors to be eliminated later, rather than a less-than-actual number of significant factors, since discovery of newly significant factors later in a study is more difficult. Therefore, the 50% upper bound was deemed acceptable and preferable to increasing the confidence level.

Utilizing the extra plates is statistically advantageous; more runs performed translates to more error degrees of freedom in the analysis, increasing the power (the probability of avoiding a type II error) of the design without modifying the significance level (the probability of a type I error), which in turn increases the likelihood of statistical significance for all factors investigated. To include the additional specimens, an experimental design was developed using D-optimality, which is a software-driven algorithm that prioritizes the stabilization of the effect coefficients. In other words, it attempts to space runs as far apart as possible in the design space (varies the runs as much as possible) to improve the significance of the effects.

From this method, it was determined that 54 runs should be performed (analogous to a full factorial plus a one-half fractional factorial) to create a balanced design space; in other words, 54 was the maximum number of runs based on materials provided that could be used without having an unbalanced design. A balanced design allows direct comparison between averages to be legitimate and meaningful, since the sample size (and thus, theoretically, the variance) for all levels of any of the four factors would be equal. Balance with respect to the hole preparation method was of additional important, since the plates were pre-drilled; half were drilled only, and the other half were drilled and reamed. The number of plates in either condition could not be changed, so 9 of each plate type had to be used. This balance is confirmed by tabulating the number of plates in each condition, as shown in Table V by an equal number of runs in each column. Since the design is not evenly replicated (not a multiple of a full factorial), the contents of each cell are not equal.

Table V: Number of Runs Per Factor Combination

		Plate Material					
		Al 7050 – T7451		Ti – 6Al – 4V (mill annealed)		PH13 – 8Mo – H1000	
		Hole Preparation		Hole Preparation		Hole Preparation	
Fastener Material	Lubrication	Drill Only	Drill and Ream	Drill Only	Drill and Ream	Drill Only	Drill and Ream
Ti – 6Al – 4V	Yes	2	1	2	1	1	2
	No	1	2	1	2	2	1
A286	Yes	2	1	1	2	1	2
	No	1	2	2	1	2	1
HSS	Yes	1	2	2	1	2	1
	No	2	1	1	2	1	2

Since the design had the proper number of plates in either condition (level of fastener hole preparation method), the design was analyzed for efficiency. This was done by looking at the D-optimal efficiencies and a power analysis of the design, as shown in Figure 7. Of importance are the design efficiencies (D, G, and A; the closer to 100%, the more efficient and thus better), the significance level being used, the signal-to-noise ratio (anticipated ratio of effect variance to variance among runs with identical treatments), and the resulting lower bounds on the power for each effect.

Design Diagnostics	
D Optimal Design	
D Efficiency	98.13218
G Efficiency	91.66552
A Efficiency	96.18993
Average Variance of Prediction	0.385041
Design Creation Time (seconds)	0

Power Analysis	
Significance Level	0.05
Signal to Noise Ratio	1
Error Degrees of Freedom	34

Effect	Power Lower Bound	Numerator DF
Plate Mat'l	0.847	2
Pin Mat'l	0.847	2
Lubrication	0.941	1
Hole Preparation	0.941	1
Plate Mat'l*Pin Mat'l	0.736	4
Plate Mat'l*Lubrication	0.817	2
Plate Mat'l*Hole Preparation	0.817	2
Pin Mat'l*Lubrication	0.817	2
Pin Mat'l*Hole Preparation	0.817	2
Lubrication*Hole Preparation	0.92	1

Figure 7: Experimental Design Analysis. Since all efficiency criteria are above 90%, the design is said to be highly efficient. Also, most powers are above 80%, signifying an effective design with respect to statistical power.

After determining the design was feasible, efficient, and effective, the design was generated, and the run order randomized and determined. The generated design of this experiment is shown in Table VI.

Table VI: Generated Run Order from Design of Experiments

STD Order	Run Order	Plate Mat'l	Plate #	Pin Mat'l	Pin #	Lubrication	Hole Preparation	STD Order	Run Order	Plate Mat'l	Plate #	Pin Mat'l	Pin #	Lubrication	Hole Preparation
52	1	Ti 6/4	9	Ti 6/4	1	Yes	E	17	28	Al 7050	14	Ti 6/4	9	Yes	B
18	2	Al 7050	3	Ti 6/4	6	Yes	A	8	29	Al 7050	1	HSS	18	No	A
43	3	Ti 6/4	1	HSS	3	No	E	54	30	Ti 6/4	10	Ti 6/4	19	Yes	F
42	4	Ti 6/4	15	A286	9	Yes	F	3	31	Al 7050	8	A286	19	No	A
23	5	Ph13-8mo	8	A286	4	Yes	C	20	32	Ph13-8mo	16	A286	11	No	D
10	6	Al 7050	9	HSS	4	Yes	A	6	33	Al 7050	17	A286	3	Yes	B
35	7	Ph13-8mo	12	Ti 6/4	18	Yes	D	36	34	Ph13-8mo	13	Ti 6/4	10	Yes	D
7	8	Al 7050	6	HSS	15	No	A	31	35	Ph13-8mo	1	Ti 6/4	14	No	C
45	9	Ti 6/4	20	HSS	10	No	G	26	36	Ph13-8mo	17	HSS	5	No	D
48	10	Ti 6/4	12	HSS	1	Yes	F	1	37	Al 7050	11	A286	13	No	B
9	11	Al 7050	4	HSS	12	No	A	24	38	Ph13-8mo	19	A286	5	Yes	D
27	12	Ph13-8mo	18	HSS	19	No	D	29	39	Ph13-8mo	7	HSS	2	Yes	C
53	13	Ti 6/4	3	Ti 6/4	5	Yes	E	22	40	Ph13-8mo	10	A286	17	Yes	C
2	14	Al 7050	2	A286	2	No	A	13	41	Al 7050	12	Ti 6/4	15	No	B
15	15	Al 7050	13	Ti 6/4	11	No	B	39	42	Ti 6/4	14	A286	20	No	F
40	16	Ti 6/4	4	A286	18	Yes	E	47	43	Ti 6/4	7	HSS	20	Yes	E
12	17	Al 7050	18	HSS	8	Yes	B	4	44	Al 7050	5	A286	1	Yes	A
14	18	Al 7050	15	Ti 6/4	20	No	B	41	45	Ti 6/4	16	A286	16	Yes	G
30	19	Ph13-8mo	15	HSS	6	Yes	D	28	46	Ph13-8mo	2	HSS	9	Yes	C
37	20	Ti 6/4	2	A286	6	No	E	25	47	Ph13-8mo	4	HSS	11	No	C
34	21	Ph13-8mo	11	Ti 6/4	17	Yes	D	44	48	Ti 6/4	18	HSS	16	No	G
46	22	Ti 6/4	8	HSS	13	Yes	E	21	49	Ph13-8mo	6	A286	14	No	C
16	23	Al 7050	10	Ti 6/4	8	Yes	B	38	50	Ti 6/4	6	A286	12	No	E
50	24	Ti 6/4	13	Ti 6/4	3	No	F	5	51	Al 7050	16	A286	15	Yes	B
32	25	Ph13-8mo	14	Ti 6/4	7	No	D	11	52	Al 7050	7	HSS	7	Yes	A
19	26	Ph13-8mo	3	A286	10	No	C	33	53	Ph13-8mo	5	Ti 6/4	12	No	C
49	27	Ti 6/4	5	Ti 6/4	13	No	E	51	54	Ti 6/4	11	Ti 6/4	2	No	F

It is important to note that the Hole Preparation column contains 7 levels (A through G). This is because the samples were not labeled upon shipment. Therefore, no two groups could be said to be the same level of hole preparation. Instead, the plates of each material were randomized into the run order in order to reduce the chance of any inexplicable factors affecting the results. The hole preparation method was therefore ignored in the run order and would instead be determined later, based on the relative responses of the two levels from the analysis.

Also, the corrosion inhibitor was applied at a thickness of approximately 2 mil or greater, as per MIL-PRF-16173 E. Unfortunately, this meant the HSS pins could not fit into the hole in the plate, since the minimum clearance for the fastener in the plate specimen hole is .001” (ASTM E238, 2008) . Therefore, all HSS pins were cleaned prior to use. This deviates from the experimental design as well, which is not ideal. However, there was no viable way to permit the coating to clear the edges of the hole, so this modification had to be made.

In light of these two alterations, the finalized testing matrix is shown below in Table VII.

Table VII: Final Run Order for Experimentation

STD Order	Run Order	Plate Mat'l	Plate #	Pin Mat'l	Pin #	Lubrication	STD Order	Run Order	Plate Mat'l	Plate #	Pin Mat'l	Pin #	Lubrication
52	1	Ti 6/4	1	Ti 6/4	1	Yes	17	28	Al 7050	14	Ti 6/4	9	Yes
18	2	Al 7050	3	Ti 6/4	6	Yes	8	29	Al 7050	1	HSS	18	No
43	3	Ti 6/4	9	HSS	3	No	54	30	Ti 6/4	10	Ti 6/4	19	Yes
42	4	Ti 6/4	15	A286	9	Yes	3	31	Al 7050	8	A286	19	No
23	5	Ph13-8mo	8	A286	4	Yes	20	32	Ph13-8mo	16	A286	11	No
10	6	Al 7050	9	HSS	4	No	6	33	Al 7050	17	A286	3	Yes
35	7	Ph13-8mo	12	Ti 6/4	18	Yes	36	34	Ph13-8mo	13	Ti 6/4	10	Yes
7	8	Al 7050	6	HSS	15	No	31	35	Ph13-8mo	1	Ti 6/4	14	No
45	9	Ti 6/4	20	HSS	10	No	26	36	Ph13-8mo	17	HSS	5	No
48	10	Ti 6/4	12	HSS	1	No	1	37	Al 7050	11	A286	13	No
9	11	Al 7050	4	HSS	12	No	24	38	Ph13-8mo	19	A286	5	Yes
27	12	Ph13-8mo	18	HSS	19	No	29	39	Ph13-8mo	7	HSS	2	No
53	13	Ti 6/4	3	Ti 6/4	5	Yes	22	40	Ph13-8mo	10	A286	17	Yes
2	14	Al 7050	2	A286	2	No	13	41	Al 7050	12	Ti 6/4	17	No
15	15	Al 7050	13	Ti 6/4	11	No	39	42	Ti 6/4	14	A286	20	No
40	16	Ti 6/4	4	A286	18	Yes	47	43	Ti 6/4	7	HSS	20	No
12	17	Al 7050	18	HSS	8	No	4	44	Al 7050	5	A286	1	Yes
14	18	Al 7050	15	Ti 6/4	20	No	41	45	Ti 6/4	16	A286	16	Yes
30	19	Ph13-8mo	15	HSS	6	Yes	28	46	Ph13-8mo	2	HSS	9	No
37	20	Ti 6/4	2	A286	6	No	25	47	Ph13-8mo	4	HSS	11	No
34	21	Ph13-8mo	11	Ti 6/4	15	Yes	44	48	Ti 6/4	18	HSS	16	No
46	22	Ti 6/4	8	HSS	13	No	21	49	Ph13-8mo	6	A286	14	No
16	23	Al 7050	10	Ti 6/4	8	Yes	38	50	Ti 6/4	6	A286	12	No
50	24	Ti 6/4	13	Ti 6/4	3	No	5	51	Al 7050	16	A286	15	Yes
32	25	Ph13-8mo	14	Ti 6/4	7	No	11	52	Al 7050	7	HSS	7	No
19	26	Ph13-8mo	3	A286	10	No	33	53	Ph13-8mo	5	Ti 6/4	12	No
49	27	Ti 6/4	5	Ti 6/4	13	No	51	54	Ti 6/4	11	Ti 6/4	2	No

Raw Data

From the experimental design shown in Table VII and utilizing the sample preparation outlined by this study, The plate specimen and fastener (either coated or uncoated) to be tested were loaded into the fixturing and then tested. The data was arranged into load-extension curves, like the one shown in Figure 6. In order to simplify the determination of bearing strength, bearing yield strength, and bearing stiffness from these curves, the curves were grouped together into six groups of 9 curves. A typical example of one of these nine-in-one plots is shown in Figure 8. The runs referred to in Figure 8 are runs 10 through 18.

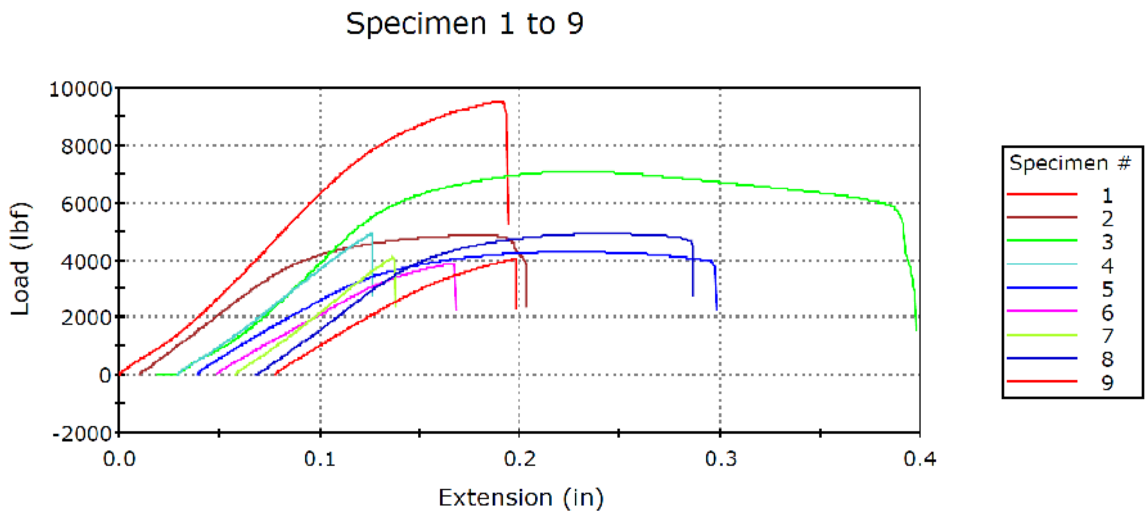


Figure 8: Typical load-extension plot, showing nine runs. Specimen 1 through 9 correspond to runs 10 through 18 in this case. Curves are offset by extension for simplicity; all extensions began at 0”.

Many important characteristics can be seen from these plots. Firstly, the ultimate tensile can be seen as the highest point along each curve. This point could be at the point of failure, like specimen 1 in Figure 8, or at a lower extension than the point of failure, like specimen 2. The ultimate tensile load occurred at the point of failure for one of two reasons: either the fastener failed, as is the case with the majority of runs using either screw type, or the plate material exhibited significant work hardening, a behavior shown in the Ti – 6Al – 4V plate specimens using HSS pins.

Secondly, the yield response is exhibited in the shape of the curve. The Al 7050 – T7451 plates showed significant yielding with either the HSS pins, like specimen 8 in Figure 8, or either screw type, like the A286 screw used in specimen 5 in Figure 8. The PH13 – 8Mo – H1000 specimens also yielded significantly, albeit with a higher ultimate tensile load and extension at failure, when using the HSS pins. Steels are known to be stronger and tougher than aluminum alloys, and these two properties can be seen by the differences in the load-extension curves alone.

Also, two of the 54 samples slipped while being tested. Although not ideal, bearing stiffness could still be determined, since proportionality was still displayed at lower loads and extensions than when the slippage occurred. The bearing strength and bearing yield strength were still determined normally, using randomization and a reasonable sample size to mitigate the effect of potentially false readings.

Once the ultimate tensile load, yield load, upper and lower stiffness loads, and upper and lower stiffness extensions were determined for each run (via the method outlined in Figure 6), the bearing strength, bearing yield strength, and bearing stiffness for each run could be determined and used for analysis.

Bearing Test Analysis Assumption Check

Once all the testing was completed and the bearing properties were determined, the experiment could be analyzed using the ANOVA approach, assuming the underlying assumptions of ANOVA were met. In order to check these assumptions, normality, equal variance, and randomization all needed to be checked for each of the three responses: bearing strength, bearing yield strength, and bearing stiffness.

In order to check normality, a normal probability distribution plot was used. Since the plate and pin materials are hypothesized to have a much more profound effect on the responses than the hole preparation method or lubrication, the data was grouped by plate and fastener material, then analyzed for normality. Such a plot is shown in Figure 9. A p-value greater than 0.01 represents a distribution of data that cannot be assumed to deviate from normality.

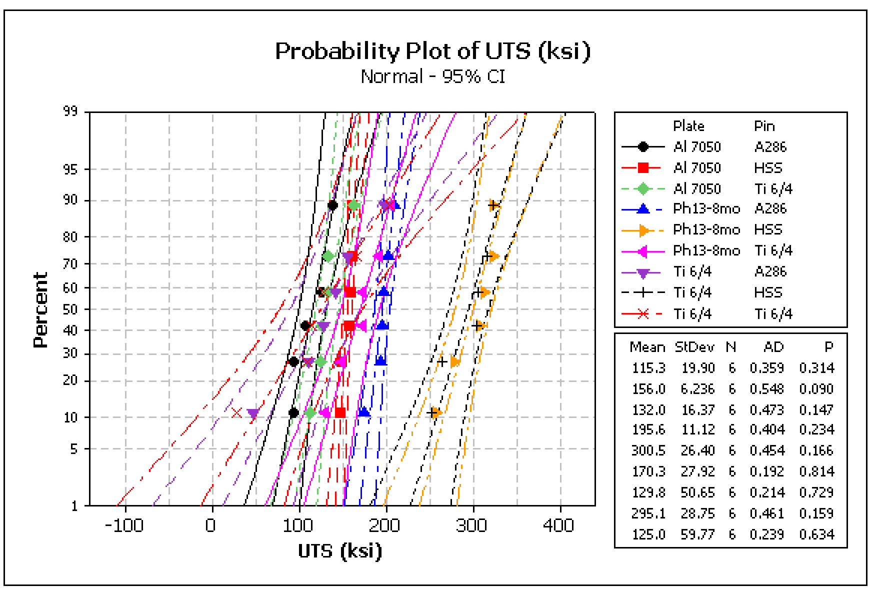


Figure 9: Normal probability distribution plot for bearing strength. Since all p-values (lower right panel) are greater than 0.01, all data are assumed to be normally distributed within their respective groups (upper right panel).

Since all three plots suggest normality, the assumption of equal variance can be tested. This is done by using Levene's test for equal variances, as shown in the plot in Figure 10. High p-values represent a grouping of data with equal variances.

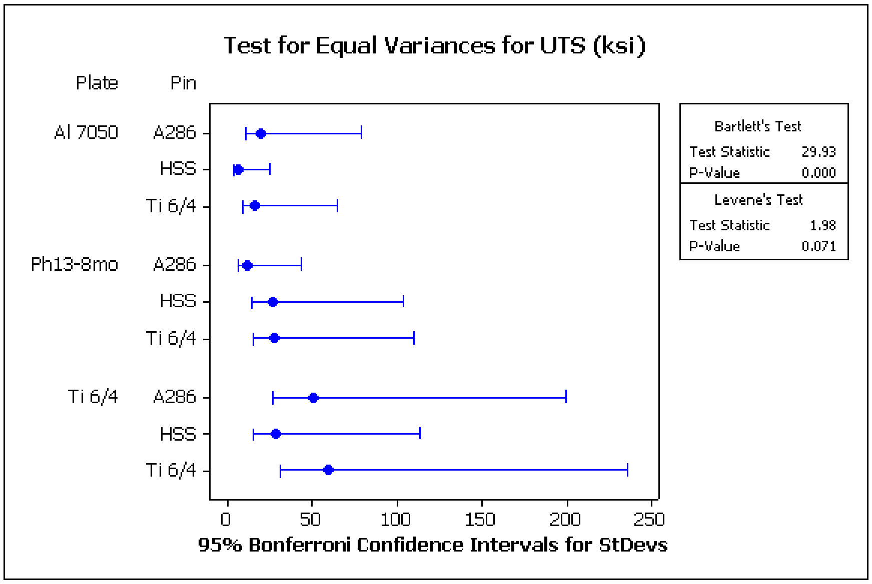


Figure 10: Levene's test for equal variances plot for bearing strength. A p-value greater than 0.01 suggests equal variance among groups.

A full tabulation of all relevant p-values for the normality tests as well as the equal variances is shown in Table VIII, showing that the vast majority of samples do not appear to violate the underlying assumptions of ANOVA. Even though the p-value for normality of bearing stiffness for Al 7050 – T7451 plates with coated A286 screws is significant, ANOVA is robust to errors caused by violated assumptions. Therefore, the analysis can still continue even if one of the assumptions is violated in one isolated case.

Table VIII: Collection of P-values for ANOVA Assumptions

Test		P-value		
		Bearing Strength	Bearing Yield Strength	Bearing Stiffness
Normality	Al7050 x A286	0.314	0.635	0.137
	Al7050 x HSS	0.090	0.718	0.024
	Al7050 x Ti 6/4	0.147	0.162	< 0.005
	PH13-8Mo x A286	0.234	0.234	0.021
	PH13-8Mo x HSS	0.166	0.075	0.106
	PH13-8Mo x Ti 6/4	0.814	0.814	0.761
	Ti 6/4 x A286	0.729	0.729	0.273
	Ti 6/4 x HSS	0.159	0.183	0.050
	Ti 6/4 x Ti 6/4	0.634	0.634	0.023
Equal variances, Levene's		0.071	0.039	0.509

Again, since nearly all tests suggest equal variances, the efficacy of randomization can be determined. This is a strictly graphical test, and does not have an associated p-value. Instead, a plot of residuals (the difference between the predicted value for a treatment combination and the actual value) versus run order is used. If there is any increase or decrease in the variance as a function of run order, the plot will show "fanning," implying that randomization was either not properly done or was ineffective. Commonly the residuals vs order plot is included in 4-in-1 plots, which also show a normal probability plot, a histogram of the residuals, and a residual vs fitted value plot (which should also be without fanning). These 4-in-1 plots make checking assumptions more intuitive; the 4-in-1 plot for the bearing strength is shown in Figure 11.

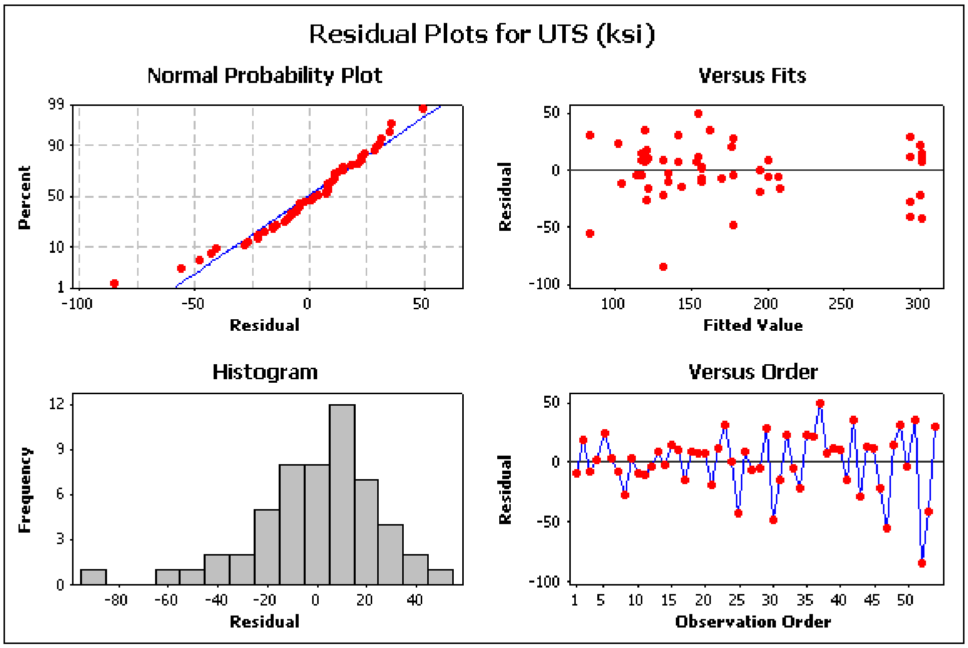


Figure 11: 4-in-1 plot for bearing strength. Since the residual vs order plot (lower right) shows no overall fanning, the residuals are thought to be random, and so randomization was effective.

Since the residuals versus order plot in Figure 11, and indeed in the residuals vs order plots for bearing yield strength and bearing stiffness, shows no significant fanning effect, it can be determined that randomization was effective. This means that no unexpected factors, like machine warm-up or operator-based biases, were introduced in such a way as to affect the results. If they had had a significant effect that wasn't countered by randomization, the response would change over time in a way not explained by the factors being studies. This would cause the absolute value of the residuals (and also the resulting variance) to increase over time, resulting in the observation of fanning.

Analysis of Variance

Since all three assumptions for ANOVA are sufficiently met, the traditional analysis can be performed. Even though the HSS pins were all without coating, the main effect by itself can be checked. However, the interaction between fastener material and lubrication cannot, and so was temporarily removed from the analysis. Also, in order to analyze the hole preparation method, the two methods had to be determined for each specimen. This was done by analyzing the hole preparation main effect plot (Figure 12).

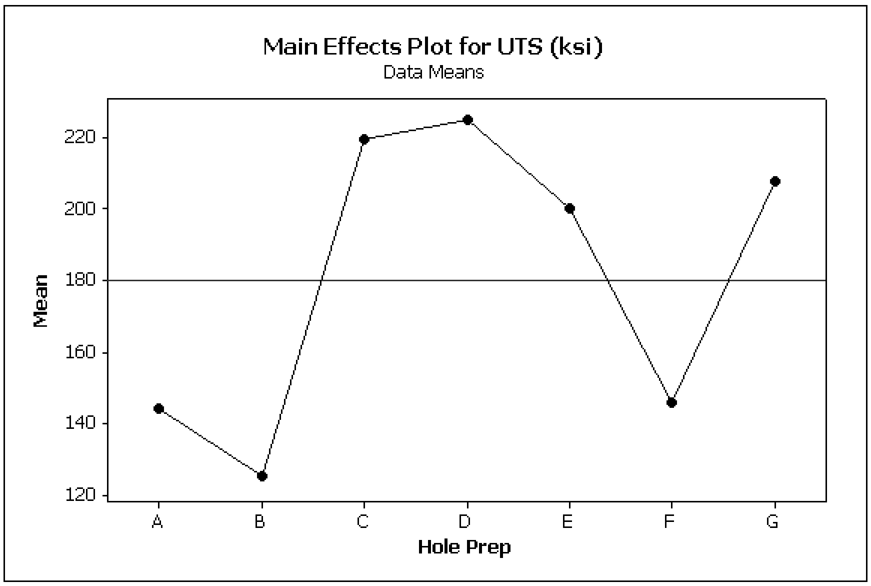


Figure 12: Main effects plot for hole preparation method's effect on bearing strength. The relative values were used to reduce the 7 methods down to the two that were intended by the project.

Since cold work could have an effect on the observed bearing strength of the specimen, the higher mean value for the Al 7050 – T7451 samples (A/B), the PH13 – 8Mo – H1000 samples (C/D), and the Ti – 6Al – 4V samples (E/F/G) was assumed to represent the drilled and reamed samples, while the lower mean represented the samples that were only drilled. Since less material would be removed in the plates that were only drilled, there would be a potential for less cold work along the surface of the hole. This would mean there was less strengthening due to cold work, and would thus have a lower average strength. In the case of the Ti – 6Al – 4V samples, which had 3 means, the two most closely grouped, E and G, were thought to be the same treatment. It was know that the samples in group G were drilled and reamed (since they came in a separate, drilled-and-reamed-only shipment); therefore, the above hypothesis appears to be reasonable. As a result, the group with the higher mean bearing strength became hole preparation method A, while the lower became hole preparation method B. However, even if the above hypothesis was deemed to be unreasonable, the effect on the response would remained unchanged. Instead, hole preparation method A would represent the holes that were only drilled; them effect observed would remain unchanged.

After reducing the levels of hole preparation and excluding the pin material/lubrication two-way interaction, the ANOVA could be performed. One was performed for each of the three responses, and the effects with significant p-values (those with $p < \alpha = 0.05$) were highlighted in Table IX.

Table IX: ANOVA P-Values for All Three Responses, Significant Values Shown in Green.

Effect	P-value Strength	Yield	Stiffness
Plate Material	0.000	0.000	0.000
Pin Material	0.000	0.000	0.000
Lubrication	0.622	0.670	0.242
Hole Preparation (Reduced)	0.493	0.794	0.504
Plate x Pin	0.000	0.000	0.301
Plate x Lubrication	0.243	0.208	0.901
Plate x Hole Prep.	0.895	0.925	0.695
Pin x Hole Prep.	0.027	0.038	0.331
Lubrication x Hole Prep	0.113	0.076	0.108

From Table IX it can be seen that the plate material main effect and pin material main effect are significant in all three responses, and the plate material/pin material and pin material/hole preparation method two-way interactions are also significant, but neither are significant effects on the bearing stiffness. Also from the ANOVA, the standard deviation for each response can be determined. The standard deviation for bearing strength was 30.2044, 29.4149 for bearing yield strength, and 70.6052 for bearing stiffness.

It can also be seen that the lubrication/hole preparation method two-way interaction has a low, albeit insignificant, p-value for all three responses. This means that although there appears to be no effect in this study, it might deserve further, more careful investigation if that effect is either desirable or of particular interest. To determine if the lubrication/hole preparation method two-way interaction is feasible to investigate in a related study, a two-way T test power analysis can be performed. Using the pooled standard deviation (the standard deviation for the entire ANOVA model) and a power of 0.90 (confidence level, $\alpha = 0.05$), the necessary sample size can be estimated given the difference in means. Utilizing the greatest difference between two means with different combinations of lubrication and hole preparation method, the necessary sample size can be determined (shown in Table X).

Table X: Power Analysis for Lubrication/Hole Preparation Method Two-way Interaction

	Lubr	Hole Prep	Mean	Difference	Pooled SD	Sample Size
Bearing Strength	N N Y Y	A B A B	209.6 173.0 155.1 151.0	36.6 17.9 4.1	72.0397	83
Bearing Yield Strength	N N Y Y	A B A B	187.6 158.8 148.7 146.9	28.8 10.1 1.8	64.0394	105
Bearing Stiffness	N N Y Y	A B A B	522.3 459.7 462.3 433.3	62.6 -2.6 29.0	164.458	147

As shown, the necessary sample size to detect at least one difference in the means (based on the pooled standard deviation from this study) of bearing strength would be 83 samples. Since there are two levels for both lubrication and hole preparation method, the total number of runs and samples would be 83 x 4 = 332. Similarly, 420 runs would be necessary for the bearing yield strength and 588 runs for the bearing stiffness. Therefore, to determine the significance of this effect, a sample size of the minimum of these three sizes, or 332 runs (significantly more than the number of runs in this study), would be needed. Otherwise, as is the case here, no effect would be observed.

Also of importance in Table IX is the fact that even though hole preparation method does not have a significant main effect, it does have a significant two-factor interaction. This means that by itself, it does not seem to have an effect on bearing strength, bearing yield strength, or bearing stiffness, but it does have an effect when another factor (in this case, the fastener used) changes.

Next, the fasteners can be compared without use of the HSS pins. This allows for a direct comparison between the performances of the two screws. The most intuitive comparison is by that of a box plot, like the one for bearing strength shown in Figure 13. As shown, there is significant overlap between the two pin types, even with lubrication taken into account. Therefore, the performance of each screw type is statistically similar to one another, and thus can be used interchangeably (with respect to the three responses).

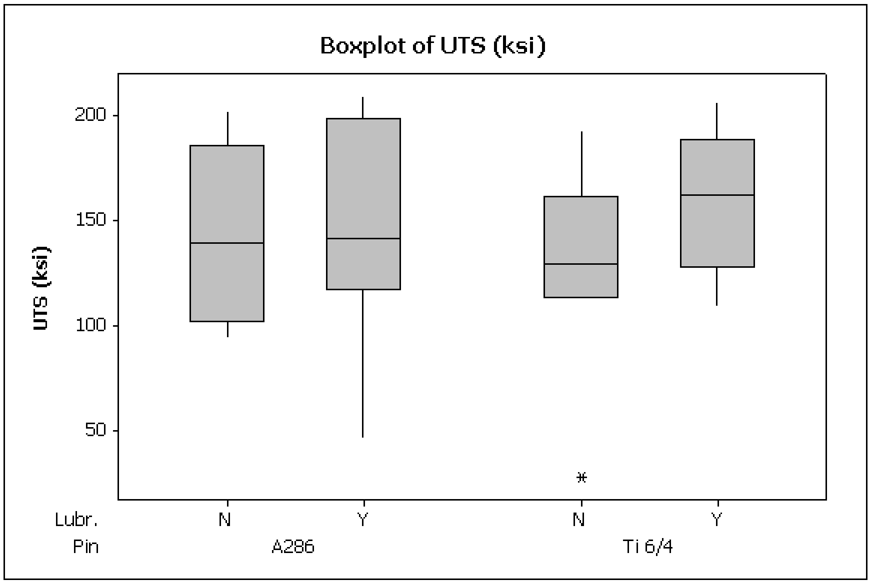


Figure 13: Boxplot for mean bearing strength, grouped by lubrication and screw type. Since the groups show significant overlap, the groups can be considered statistically similar.

Another way to quantitatively compare the two groups is by performing a two-sample t test. This test uses the difference of the two means and the standard deviations for each screw type to develop a confidence interval on the difference of means. A p-value is then determined by the ratio of the maximum value to the minimum value; a range that is both positive and negative signifies an insignificant result. The actual values used in this two-sample t test are shown in Figure 14.

```
Two-Sample T-Test and CI: UTS (ksi), Pin

Two-sample T for UTS (ksi)

Pin      N   Mean  StDev  SE Mean
A286    18  146.9   46.9       11
Ti 6/4  18  142.4   42.2      9.9


Difference = mu (A286) - mu (Ti 6/4)
Estimate for difference:  4.5
95% CI for difference:  (-25.8, 34.7)
T-Test of difference = 0 (vs not =): T-Value = 0.30
P-Value = 0.766  DF = 33
```

Figure 14: Minitab © output for a two-sample t test. Shown is the estimated difference, t-value, and insignificant p-value.

As given by the p-value, there is a 76.6% chance that any difference in the means of the two screws is due to random chance, and is thus unlikely to occur intentionally. Therefore, this again shows that the two screw types are statistically similar.

In conclusion, the plate material and fastener chosen seem to have an effect on bearing strength and bearing yield strength, while the hole preparation method also has an effect, depending on the fastener chosen. Alternatively, only the plate material and fastener chosen, independently of one another, seem to have an effect on the bearing stiffness. Also, only the fastener type (pin or screw) in this study seems to affect the results, not the fastener material.

Additionally, when the standard deviations are compared to the means for each group, it can be seen that the standard deviations are sufficiently low. Because of this, effects could be determined from the ANOVA. It can therefore also be said that ASTM specification E238 – 84(08) is a precise test method. A decent standard deviation is attributed to the precision. Also, the precision was sufficient to allow for the observation of some effects via ANOVA, attributing to the precision of both this study and the specification.

DISCUSSION

Qualifying

As shown in Table II, the Al 7050 – T7451 plates had significantly more scatter (a greater standard deviation) in the hardness data than the other two plate materials. This is likely due to being at the upper limit of the HRB scale. Since the hardness of the Al 7050 – T7451 plates is at the upper end of the scale, damage to the sample from testing (size of the dimples) is minimal. This would mean that a slight dimensional change in the localized yielding region would cause a significant areal change. Therefore, a large change in hardness would be observed. This is the reason why data at the extremes, especially the upper extreme, are considered unreliable.

Also, the Al 7050 – T7451 plates exceeded the hardness outlined by AMS 2658B. This is perhaps due to heat treatment deviation, but is difficult to say without access to material certifications. This could also be why the Ti – 6Al – 4V (mill annealed) samples fell short of the hardness value outlined by the Aerospace Structural Metals Handbook (Code 3707) and the PH13 – 8Mo – H1000 samples fell short of the value outlined by AMS 5629. However, as previously stated, the HRC hardness value for the Ti – 6Al – 4V plates is approximate and is not used for acceptance.

The Ti – 6Al – 4V and A286 screws have a significantly lower hardness than the HSS pins, as displayed in Table III. The pins are meant to be a control for the test, whereas the screws are manufactured and intended for application. For the purposes of this ASTM specification E238 – 84(08) testing, the hardness requirements, and thus heat treatment requirements, for the pins are much higher than for the screws. As stated previously, this is ideal; the purpose of the pins is to cause the plate to fail with virtually no damage to the pin. Conversely, the screws are supposed to fail before the plate. This allows lighter, less expensive screws to be used to the same effect. Therefore, it is much more realistic for the screws to be less hard than the pins.

Testing

An important observation from the testing is that all Al 7050 – T7451 specimens yielded prior to failure. This is typical for wrought aluminum alloys, like Al 7050. Since aluminum forms a face-centered cubic (FCC) crystal structure, dislocations move easily in response to stress (FCC crystals are associated with a low Peierls stress and many active slip systems). This leads to a lower strength and a higher ductility than an equivalent material of a different crystal structure, like body-centered cubic or hexagonal close-packed. The ductility of aluminum alloys can be witnessed in the fracture surface, like the one in Figure 15.

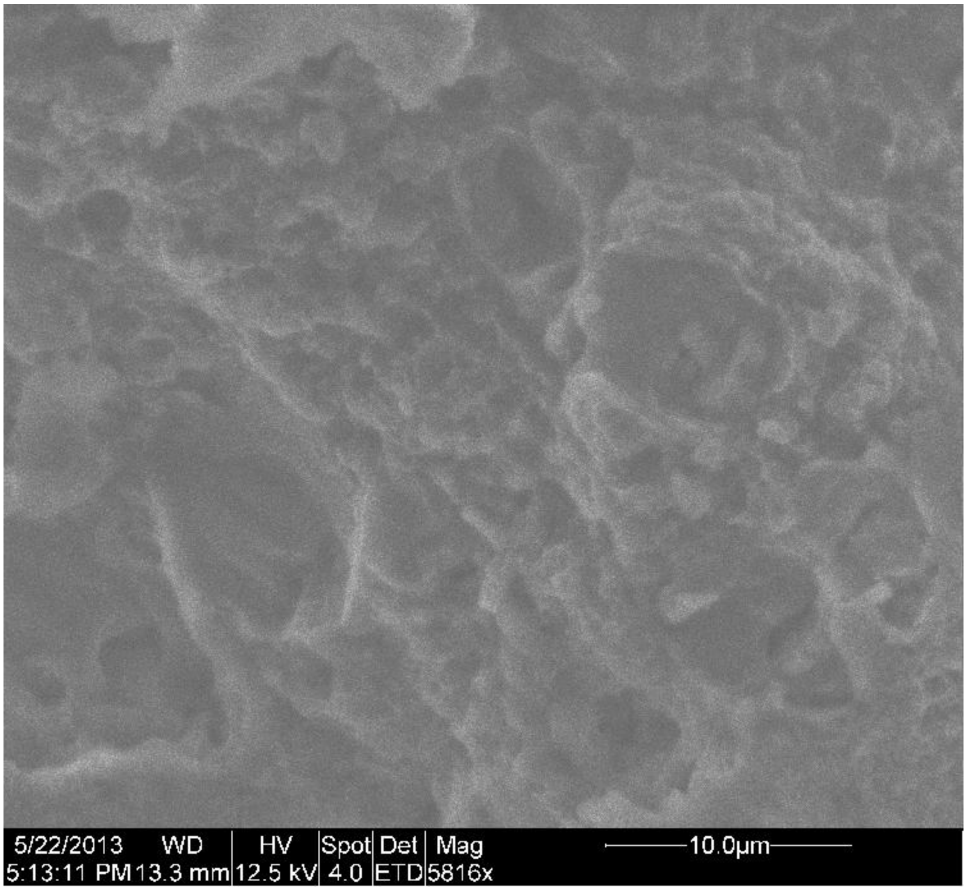


Figure 15: Scanning electron micrograph of the fracture surface of one of the Al 7050 – T7451 plate specimens. The dimples seen suggest microvoid coalescence, a common ductile fracture mechanism.

The heat treatment for these plates, temper T7451, is a stabilization heat treatment. This means that the precipitates are over-aged in order to sustain the mechanical properties (since it prevents further room temperature aging). It also improves the yield strength of the material, but to a lesser extent than strengthening heat treatments. This means that although Al 7050 – T7451 are strong, they will fail before strengthened Ti – 6Al – 4V or A286 screws. This leads to yielding of the aluminum plate prior to failure of the screws. Since these screws led to bearing strengths lower than those with the HSS pins, all Al 7050 – T7451 plates would yield before breaking.

It can also be seen from the data that all samples utilizing the HSS pins yielded before breaking. Ti – 6Al

– 4V (mill annealed) and PH13 – 8Mo – H1000, much like Al 7050 – T7451, exhibit ductile failure. This is a desirable trait for structural materials; this makes the failure more predictable than a brittle fracture with no yielding whatsoever. A yield-before-break behavior allows the user to witness the failure prior to fast fracture, providing a degree of safety. As shown in the hardness data for the Ti – 6Al – 4V (mill annealed) plates, PH13 – 8Mo – H1000 plates, and HSS pins (Table II and Table III), the pins are much harder than the plates. This would suggest that the yield strength for Ti – 6Al – 4V (mill annealed) and PH13 – 8Mo – H1000 is lower than HSS, meaning that the plates should fail prior to the pins. This trend was observed, and ductile fracture is observed in the fracture surface of the plates, like in the Al 7050 – T7451 plates (Figure 15). The fracture surfaces for the Ti – 6Al – 4V and PH13 – 8Mo – H1000 plates can be seen in Figure 16.

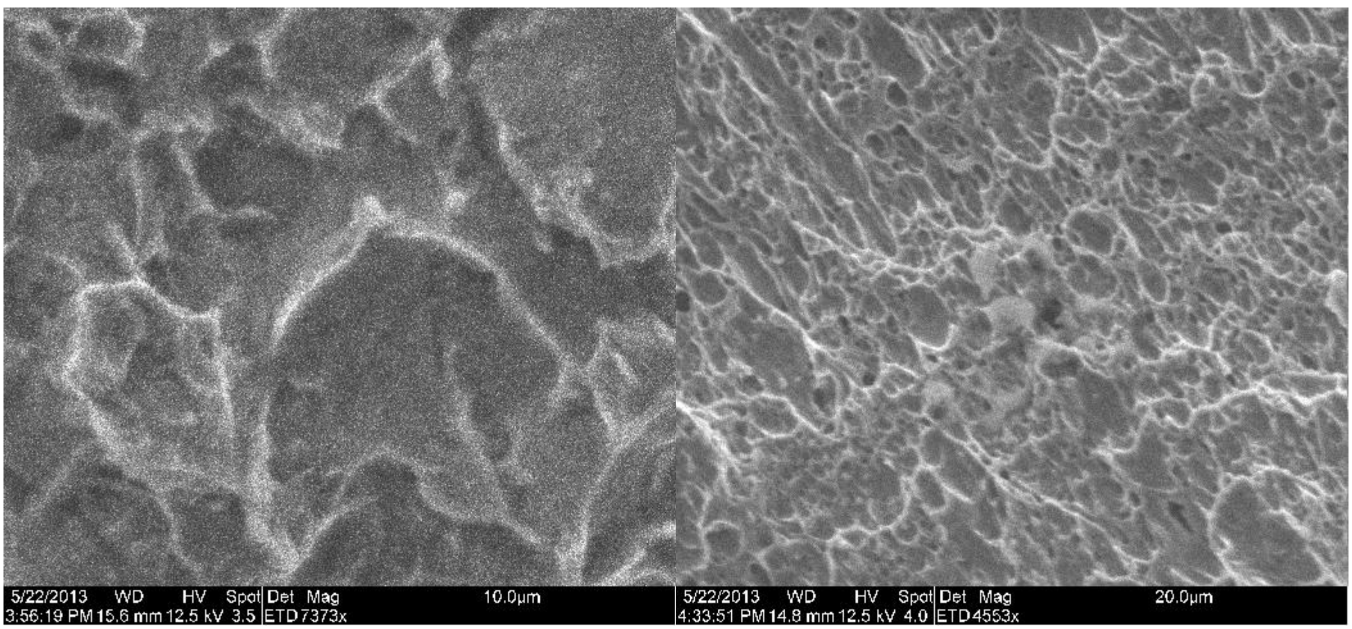
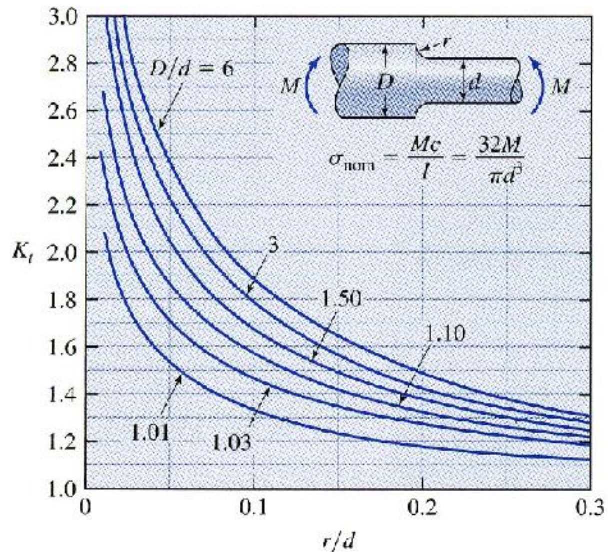


Figure 16: Scanning electron micrographs of a typical Ti – 6Al – 4V plate (left) and PH13 – 8Mo – H1000 plate (right). Both micrographs show the microvoid coalescence mechanism, signifying ductile fracture.

Contrasting to the HSS pins, all A286 and Ti – 6Al – 4V screws broke prior to plate yield when a Ti – 6Al – 4V (mill annealed) or PH13 – 8Mo – H1000 plate was used. This is due to stress concentration in the screw threads. Using the nominal dimensions for a 1/4”-20 screw thread with a class 3A fit, it was determined that the ratio of major diameter to minor diameter was 1.325, and the ratio of half the thread pitch to the minor diameter was 0.132 (Machinery's Handbook, 2012). Utilizing the D/d and r/d and approximating the screw as a series of shafts with a shoulder fillet (as shaft, fillet, fillet, shaft, etc.) in bending, the stress concentration factor can be determined from a curve like the one shown in Figure 17.



Approximate formula
$K_t \approx B\left(\frac{r}{d}\right)^a$, where:

D/d	B	a
6.00	0.879	−0.332
3.00	0.893	−0.309
1.50	0.938	0.258
1.10	0.951	−0.238
1.03	0.981	−0.184
1.01	0.919	−0.170

Figure 17: Stress concentration factor curves for a shaft with a shoulder fillet, loaded in bending. (Shigley's Mechanical Engineering Design, 2011)

From the curves, the stress concentration factor, K_t, is between 1.4 and 1.6. This means that the far-field stress is amplified by 40-60% around the screw threads. Since the hardness values, and thus the yield strengths, between the two screw materials and two plate materials are similar, the amplified stress would lead to the screws failing prior to plate yielding.

Since the approximation uses rounded threads, the actual stress concentration factor would be higher. Since the HSS pins would ideally represent the performance without geometry, the stress concentration factor can be approximated by the percent difference between the screw in question and the HSS pin. Using the mean bearing strength, the HSS pins achieved a mean strength of 250.54 ksi. The approximate stress concentration factors for each screw type are shown in Table XI.

Table XI: Approximate Stress Concentration Factors by Screw Type

Screw Material	Mean Bearing Strength (ksi)	K_t
Coated A286	146.92	1.71
Ti – 6Al – 4V	142.45	1.76

Although the stress concentration factors of the two screw types are different, they are not statistically different. Therefore, it cannot be said which screw type has the greater stress concentration factor; in fact, since the geometries of the two types are nearly identical, the factors should be the same. Also, the only difference between the two screws is the material used to make them; since this only accounts for roughly a 5% difference in stress concentration, the performance of the screws is geometry-driven, and the material used is nearly insignificant by this measure. This insignificant difference can also be seen in the Rockwell hardness values for the two screw types in Table III, which shows a percent difference of less than 1% in the mean hardness values.

As shown in Table XI, the stress concentration factor is roughly 71-76% around the screw threads. However, this stress concentration is unlikely to be witness in application: ideally, the threads would not be loaded, and only the section of the fastener without threads would contact the plate or plates. However, this was not the case in this study. Since both the threaded section and the smooth section of the screws were loaded, the threaded section failed in each case, due to stress concentrations greater than 40%. This makes estimation of the performance of the screws inaccurate, since a screw would be chosen that was sufficiently long to avoid stress concentration and early failure.

Statistics

The assumption of normality was determined to be reasonable overall. However, the p-value for the bearing stiffness using Al 7050 – T7451 plate specimens with Ti – 6Al – 4V screws was significant. This is due to the nature of stiffness: it is a function of the stiffness of the atomic bonds in the material, and is thus not subject to heat treatment, cold work, or other strengthening mechanisms, like tensile strength and yield strength are. This would cause the stiffness to manifest in discrete values (ideally), rather than as a continuous variable. Therefore, it would be expected that bearing stiffness would be a less continuous variable than the bearing strength or bearing yield strength. This can be seen in Table VIII, where the p-values for all stiffness normality tests are lower than the corresponding p-value in the bearing strength and bearing yield strength tests. This difference in continuity also has an effect on the Levene's tests for equal variances, showing a significantly higher p-value.

This difference between stiffness and strength can also be witnessed in the lack of significant two-factor interactions for stiffness. In ASTM E238 tests, the fastener is pulled upward, subjecting the plate to tension. To determine bearing stiffness, this plate-pin system is only loaded in an elastic way; the pin and plate both operate similar to two linear springs. Therefore, their effects simply add to one another, so no interaction between pin and plate is witnessed. Also, cold work and lubrication have no effect on this mechanism, so neither main effect nor their respective two-factor interactions are significant. However, depending on the scatter of the data, an artificial two-factor interaction between lubrication and hole preparation method could be observed. This alludes to the observation of false effects (type II error) mentioned earlier.

Another assumption was in the hole preparation method grouping: the group with the higher mean bearing strength was drilled and reamed, while the group that was drilled only was the lower mean value (Figure 12). This assumption was made because more material would be removed from the plate during drilling and reaming than drilling alone. This would lead to increased cold work, which would increase the strength of the material around the hole. This, in turn, would lead to a higher perceived bearing strength for that particular run and sample. However, since the hole preparation method was coded as A and B during experimentation, the actual level coded to either A or B wouldn't alter the results. Therefore, A could be either drilled only or drilled and reamed, and the grouping would still be valid.

Significant Effects

The first significant main effect discovered was the plate material. Since the three materials have variations in tensile strength, yield strength, and elastic modulus, variation would also be expected in bearing strength, bearing yield strength, and bearing stiffness, respectively. The same could be said for the fastener used, the only other significant main effect, even though the two screw types behaved similarly, but quite differently from the HSS pins. The mechanical properties were more governed by the geometry of the screws than the material, causing them to behave similarly. In contrast, the HSS pins were made from a much harder material and with a less significant stress concentration factor, since deviations in the surface, or surface roughness, are much smaller and less severe than the screw threads.

As stated, the screws failed before the plates when Ti – 6Al – 4V (mill annealed) or PH13 – 8Mo – H1000 plates were used, but afterward when Al 7050 – T7451 plates were used. Also, the Samples behaved in a different way than this when the HSS pins were used. This complex relationship between plate and fastener led to a significant two-factor interaction between plate material and fastener used. This seems reasonable since the materials, and thus behaviors, varied between plate and pin materials, and geometry became a factor when screws were used.

The Ti – 6Al – 4V and A286 screw behaved similarly in most ways. However, the A286 screws and HSS pins both exhibited higher mean values with the drilled only plates than the drilled and reamed plates. However, the opposite trend was observed in the Ti – 6Al – 4V screws. The Ti – 6Al – 4V screws had a tendency to imbed themselves in the plates being tested before breaking, rather than just breaking as the A286 screws did. This imbedding would be easier with less cold work, which could lead to a higher perceived strength. Contrary to the analysis of the main effects plot shown in Figure 12, this would suggest that the drilled only plates were more strengthened than the drilled and reamed samples. This can be seen in the HSS pins (which showed no deformation or imbedding of any kind) performing better in the presumed drilled only condition. However, this trend is not backed by the statistics, since both means are statistically similar in all three responses.

CONCLUSIONS

From this study, it was determined that both the plate material used and the pin material, whether a screw or a pin, had a significant effect on ASTM E238 bearing strength, bearing yield strength, and bearing stiffness. The interaction between the two factors was also significant on all responses but the bearing stiffness. PH13 – 8Mo – H1000 plates seemed to perform best on average, followed by Ti – 6Al – 4V (mill annealed), then Al 7050 – T7451. PH13 – 8Mo – H1000 and Ti – 6Al – 4V (mill annealed) plates had similar bearing strength and bearing yield strength averages with the HSS control pins being used, which had the highest mean values for a given plate and fastener. The Ti – 6Al – 4V and A286 screws behaved and performed statistically similar in most cases.

The method by which the holes in the plates were prepared, drilled and reamed or simply drilled, was not significant by itself, but did seem to have an effect on the performance of the fastener used. The Ti – 6Al – 4V screws performed better when the hole was simply drilled, while the coated A286 screws performed better when the hole was drilled and reamed. All screws had lower resulting bearing properties than the HSS control pins.

It was also found that ASTM specification E238 – 84(08) is a precise test method, since the method could be performed repeatably and reliably with no missing data points. Therefore, this ASTM testing method is reasonable for determining bearing properties, which can then be used to design aircraft.

RECOMMENDATIONS AND FUTURE WORK

One possible improvement on the experiment outlined in this work would be to test HSS pins in a coated condition. To make this possible, smaller HSS pins would have to be used for the coated samples, and the coating process would have to be automated in order to insure a constant coating thickness. Including coated HSS pins in the model would allow for a more complete ANOVA, which could lead to more meaningful results by allowing the fastener and lubrication two-factor interaction to be observed and evaluated for all possible levels of fastener and lubrication. This could yield a significant effect for lubrication, either as a main effect or a two-factor interaction with another factor.

A potential follow up experiment could be performed utilizing more or different plate materials and fasteners. This application-based approach could yield valuable information about other plate materials and fasteners, increasing the scope of the experiment.

Conversely, the scope of this experiment could be narrowed in a future experiment. Observing only factors deemed statistically significant by this study, a more accurate p-value could be obtained. This means more information could be determined, with either the same or more runs in the experiment. For example, lubrication could be removed, since it didn't yield any statistically significant effects by itself or with other factors.

Another possible follow up study would be to narrow the study further, to look into the effect of cold work on the bearing properties. Since the main effect plot for bearing strength suggests a different trend than the trend in the fastener/hole preparation method interaction, careful investigation would be necessary to determine the more accurate trend, and thus the underlying mechanism, in the relationship between cold work and the bearing properties.

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APPENDICES

Appendix A: Testing Data

A1: Numerical Data

Table XII: Bearing Strength, Bearing Yield Strength, and Bearing Stiffness for Each Run

Run Order	Plate		Pin		Lubrication	Bearing Strength (ksi)	Bearing Yield Strength (ksi)	Bearing Stiffness (ksi)
1	Ti 6/4	1	Ti 6/4	1	Y	204.44	204.44	479.78
2	Al 7050	3	Ti 6/4	6	Y	162.05	123.16	340.93
3	Ti 6/4	9	HSS	3	N	305.44	271.87	478.85
4	Ti 6/4	15	A286	9	Y	198.32	198.32	420.17
5	Ph13-8mo	8	A286	4	Y	208.72	208.72	754.72
6	Al 7050	9	HSS	4	N	160.43	131.55	401.07
7	Ph13-8mo	12	Ti 6/4	18	Y	205.83	205.83	572.52
8	Al 7050	6	HSS	15	N	159.35	130.08	433.60
9	Ti 6/4	20	HSS	10	N	323.51	286.18	591.72
10	Ti 6/4	12	HSS	1	N	316.63	279.97	554.02
11	Al 7050	4	HSS	12	N	158.06	135.48	403.23
12	Ph13-8mo	18	HSS	19	N	323.16	282.19	909.09
13	Ti 6/4	3	Ti 6/4	5	Y	166.20	166.20	369.34
14	Al 7050	2	A286	2	N	139.08	113.21	323.45
15	Al 7050	13	Ti 6/4	11	N	126.14	126.14	322.58
16	Ti 6/4	4	A286	18	Y	141.18	141.18	420.17
17	Al 7050	18	HSS	8	N	161.72	132.61	460.83
18	Al 7050	15	Ti 6/4	20	N	132.61	109.97	322.58
19	Ph13-8mo	15	HSS	6	N	322.82	277.98	895.52
20	Ti 6/4	2	A286	6	N	127.71	127.71	438.36
21	Ph13-8mo	11	Ti 6/4	17	Y	172.31	172.31	646.90
22	Ti 6/4	8	HSS	13	N	306.32	268.46	575.54
23	Al 7050	10	Ti 6/4	8	Y	125.13	109.09	320.86
24	Ti 6/4	13	Ti 6/4	3	N	113.80	113.80	417.83
25	Ph13-8mo	14	Ti 6/4	7	N	192.54	192.54	559.70
26	Ph13-8mo	3	A286	10	N	175.51	175.51	561.80
27	Ti 6/4	5	Ti 6/4	13	N	128.99	128.99	451.98
28	Al 7050	14	Ti 6/4	9	Y	132.97	126.49	324.32
29	Al 7050	1	HSS	18	N	147.20	124.80	400.00
30	Ti 6/4	10	Ti 6/4	19	Y	109.09	109.09	413.22
31	Al 7050	8	A286	19	N	93.92	84.21	268.82
32	Ph13-8mo	16	A286	11	N	201.82	201.82	562.85
33	Al 7050	17	A286	3	Y	106.61	100.15	322.58
34	Ph13-8mo	13	Ti 6/4	10	Y	129.33	129.33	497.51
35	Ph13-8mo	1	Ti 6/4	14	N	149.05	149.05	549.45
36	Ph13-8mo	17	HSS	5	N	277.91	242.05	691.44
37	Al 7050	11	A286	13	N	93.67	90.44	293.26
38	Ph13-8mo	19	A286	5	Y	197.38	197.38	527.76
39	Ph13-8mo	7	HSS	2	N	258.57	210.36	735.29
40	Ph13-8mo	10	A286	17	Y	194.46	194.46	603.77
41	Al 7050	12	Ti 6/4	15	N	113.21	103.50	153.61
42	Ti 6/4	14	A286	20	N	110.15	110.15	416.67
43	Ti 6/4	7	HSS	20	N	265.62	236.10	599.40
44	Al 7050	5	A286	1	Y	126.31	100.40	323.45
45	Ti 6/4	16	A286	16	Y	46.29	46.29	445.10
46	Ph13-8mo	2	HSS	9	N	308.34	272.06	696.66
47	Ph13-8mo	4	HSS	11	N	312.45	271.70	754.72
48	Ti 6/4	18	HSS	16	N	253.16	231.76	593.47
49	Ph13-8mo	6	A286	14	N	195.82	195.82	555.56
50	Ti 6/4	6	A286	12	N	155.11	155.11	463.77
51	Al 7050	16	A286	15	Y	132.43	129.20	306.40
52	Al 7050	7	HSS	7	N	148.99	129.55	404.31
53	Ph13-8mo	5	Ti 6/4	12	N	172.66	172.66	454.37
54	Ti 6/4	11	Ti 6/4	2	N	27.73	27.73	105.53

A2: Load-Extension Curves

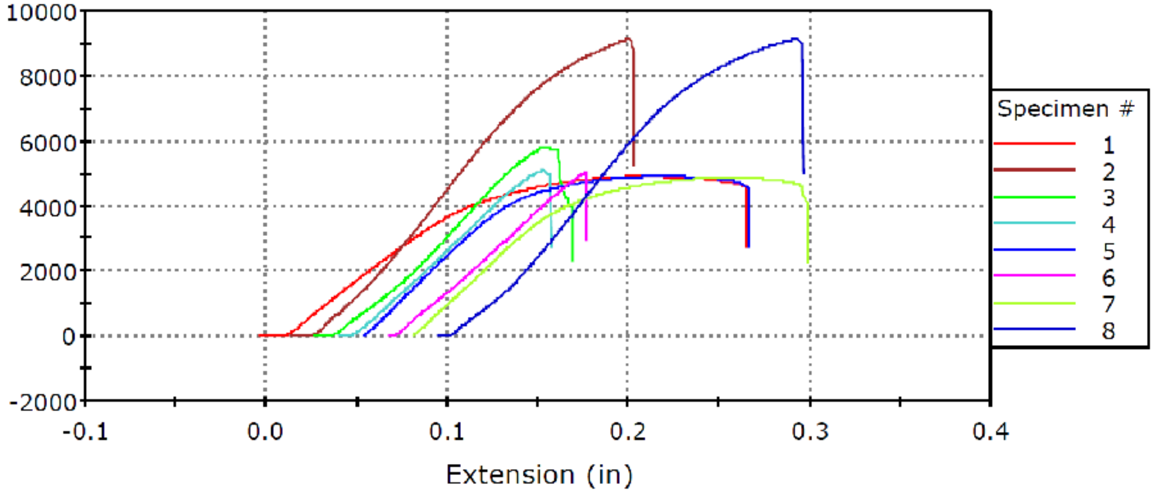

Figure 18: Load-extension curve for runs 2-9

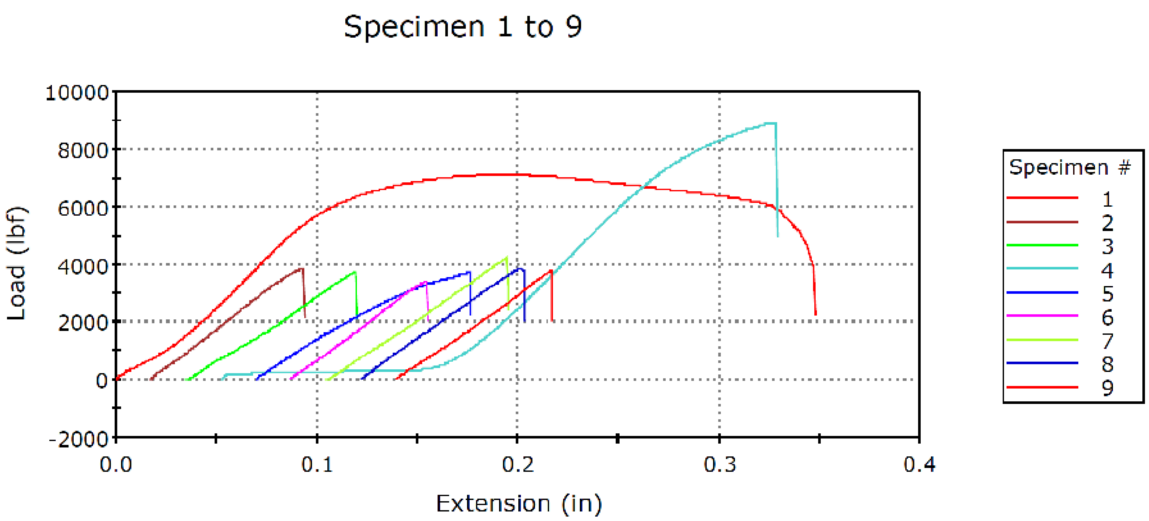

Figure 19: Load-extension curve for runs 19-27

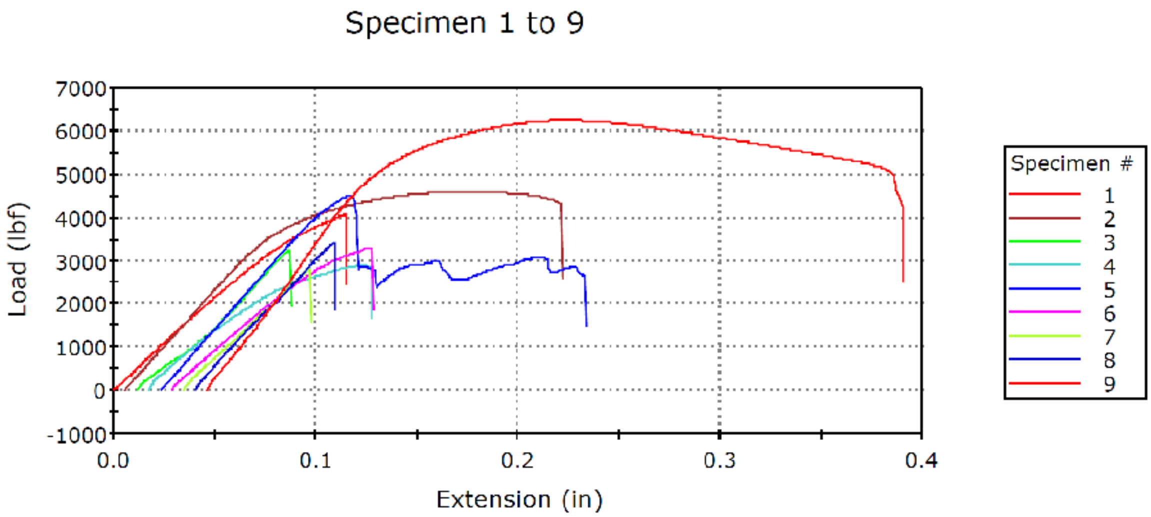

Figure 20: Load-extension curve for runs 28-36

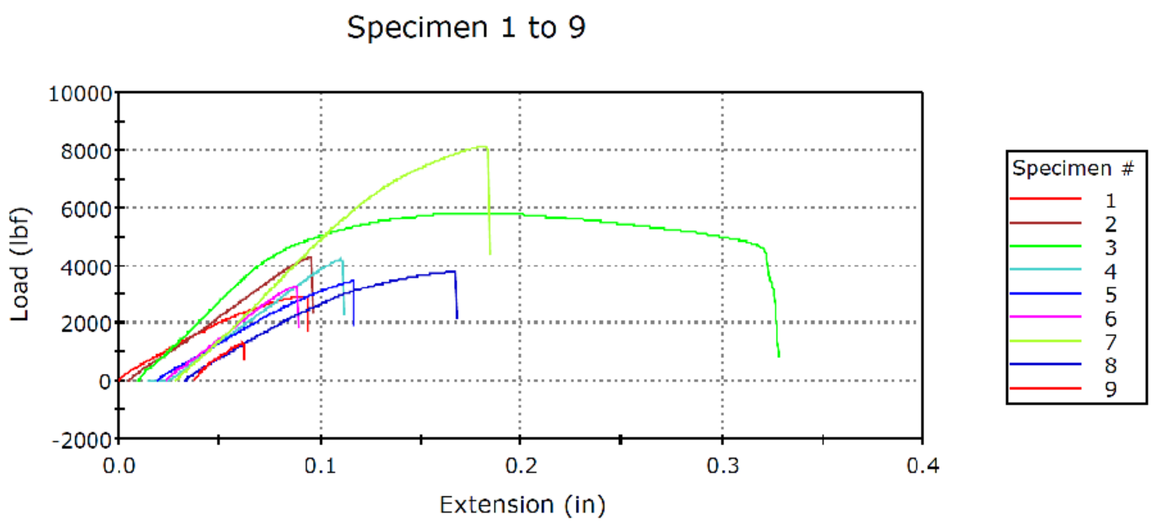

Figure 21: Load-extension curve for runs 37-45

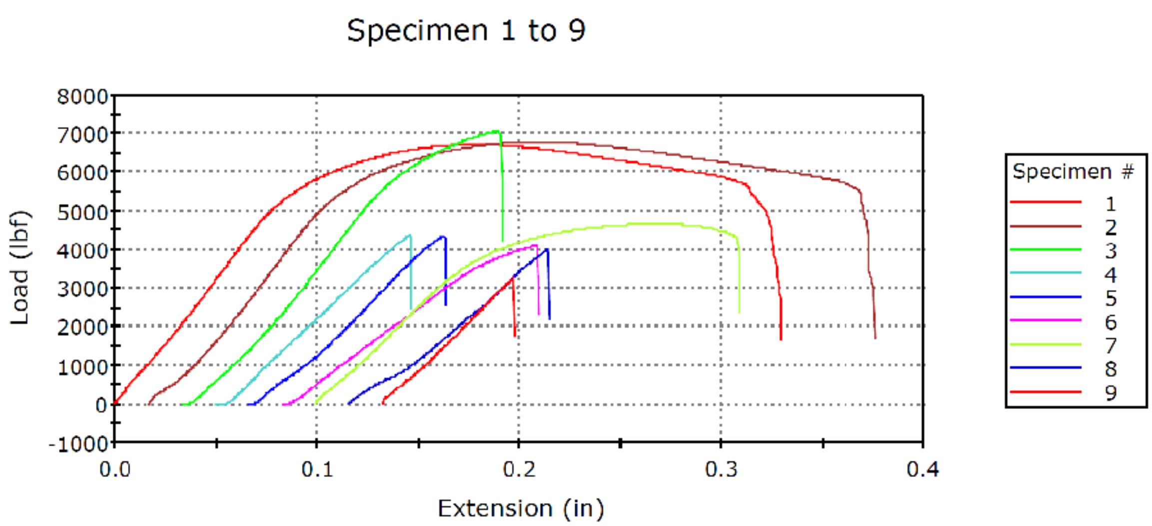

Figure 22: Load-extension curve for runs 46-54

Appendix B: Statistical Data

B1: Additional Randomization Tables

Table XIII: Plate Geometry Qualifying Order

Std Order	Test Order	Plate		Std Order	Test Order	Plate	
43	1	Ti 6/4	6	25	30	Ph13-8mo	7
45	2	Ti 6/4	8	39	31	Ti 6/4	2
34	3	Ph13-8mo	16	1	32	Al 7040-T7451	1
48	4	Ti 6/4	11	17	33	Al 7040-T7451	17
37	5	Ph13-8mo	19	38	34	Ti 6/4	1
54	6	Ti 6/4	17	8	35	Al 7040-T7451	8
29	7	Ph13-8mo	11	55	36	Ti 6/4	18
3	8	Al 7040-T7451	3	13	37	Al 7040-T7451	13
26	9	Ph13-8mo	8	36	38	Ph13-8mo	18
49	10	Ti 6/4	12	7	39	Al 7040-T7451	7
33	11	Ph13-8mo	15	4	40	Al 7040-T7451	4
51	12	Ti 6/4	14	27	41	Ph13-8mo	9
30	13	Ph13-8mo	12	53	42	Ti 6/4	16
46	14	Ti 6/4	9	42	43	Ti 6/4	5
16	15	Al 7040-T7451	16	22	44	Ph13-8mo	4
6	16	Al 7040-T7451	6	14	45	Al 7040-T7451	14
50	17	Ti 6/4	13	12	46	Al 7040-T7451	12
11	18	Al 7040-T7451	11	15	47	Al 7040-T7451	15
21	19	Ph13-8mo	3	9	48	Al 7040-T7451	9
47	20	Ti 6/4	10	18	49	Al 7040-T7451	18
10	21	Al 7040-T7451	10	20	50	Ph13-8mo	2
40	22	Ti 6/4	3	2	51	Al 7040-T7451	2
24	23	Ph13-8mo	6	57	52	Ti 6/4	20
56	24	Ti 6/4	19	28	53	Ph13-8mo	10
32	25	Ph13-8mo	14	23	54	Ph13-8mo	5
35	26	Ph13-8mo	17	41	55	Ti 6/4	4
31	27	Ph13-8mo	13	5	56	Al 7040-T7451	5
19	28	Ph13-8mo	1	52	57	Ti 6/4	15

Table XIV: Pin Straightness Qualifying Order

Std Order	Test Order	Pin	Std Order	Test Order	Pin
36	1	HSS 16	13	31	A286 13
37	2	HSS 17	11	32	A286 11
32	3	HSS 12	58	33	Ti 6/4 18
23	4	HSS 3	60	34	Ti 6/4 20
28	5	HSS 8	43	35	Ti 6/4 3
34	6	HSS 14	5	36	A286 5
29	7	HSS 9	17	37	A286 17
38	8	HSS 18	15	38	A286 15
30	9	HSS 10	42	39	Ti 6/4 2
27	10	HSS 7	14	40	A286 14
25	11	HSS 5	7	41	A286 7
21	12	HSS 1	16	42	A286 16
26	13	HSS 6	3	43	A286 3
33	14	HSS 13	54	44	Ti 6/4 14
24	15	HSS 4	56	45	Ti 6/4 16
22	16	HSS 2	20	46	A286 20
39	17	HSS 19	8	47	A286 8
31	18	HSS 11	44	48	Ti 6/4 4
35	19	HSS 15	57	49	Ti 6/4 17
40	20	HSS 20	4	50	A286 4
51	21	Ti 6/4 11	9	51	A286 9
1	22	A286 1	19	52	A286 19
59	23	Ti 6/4 19	10	53	A286 10
47	24	Ti 6/4 7	45	54	Ti 6/4 5
53	25	Ti 6/4 13	41	55	Ti 6/4 1
50	26	Ti 6/4 10	12	56	A286 12
6	27	A286 6	18	57	A286 18
48	28	Ti 6/4 8	55	58	Ti 6/4 15
49	29	Ti 6/4 9	46	59	Ti 6/4 6
52	30	Ti 6/4 12	2	60	A286 2

Table XV: Pin Coating and Testing Order

Rdm Order	Pin		Pin		Pin			
1	HSS	4	A286	1	Ti 6/4	8	Coat	Test Order
2	HSS	7	A286	15	Ti 6/4	9		
3	HSS	8	A286	3	Ti 6/4	6		
4	HSS	9	A286	17	Ti 6/4	17		
5	HSS	2	A286	4	Ti 6/4	18		
6	HSS	6	A286	5	Ti 6/4	10		
7	HSS	13	A286	18	Ti 6/4	1		
8	HSS	20	A286	16	Ti 6/4	5		
9	HSS	1	A286	9	Ti 6/4	19		
10	HSS	14	A286	8	Ti 6/4	4	Unused	
11	HSS	15	A286	13	Ti 6/4	15	Uncoated	
12	HSS	18	A286	2	Ti 6/4	20		
13	HSS	12	A286	19	Ti 6/4	11		
14	HSS	11	A286	10	Ti 6/4	14		
15	HSS	5	A286	11	Ti 6/4	7		
16	HSS	19	A286	14	Ti 6/4	12		
17	HSS	3	A286	6	Ti 6/4	13		
18	HSS	16	A286	12	Ti 6/4	3		
19	HSS	10	A286	20	Ti 6/4	2		
20	HSS	17	A286	7	Ti 6/4	16	Unused	

Table XVI: Pin Coating Order

Num Order	Coat Order	Pin		Num Order	Coat Order	Pin		Num Order	Coat Order	Pin	
1	8	A286	1	11	9	HSS	1	21	18	Ti 6/4	1
2	30	A286	3	12	28	HSS	2	22	15	Ti 6/4	4
3	14	A286	4	13	16	HSS	4	23	12	Ti 6/4	5
4	17	A286	5	14	4	HSS	6	24	29	Ti 6/4	6
5	27	A286	8	15	21	HSS	7	25	1	Ti 6/4	8
6	3	A286	9	16	19	HSS	8	26	10	Ti 6/4	9
7	26	A286	15	17	22	HSS	9	27	5	Ti 6/4	10
8	13	A286	16	18	25	HSS	13	28	23	Ti 6/4	17
9	2	A286	17	19	24	HSS	14	29	20	Ti 6/4	18
10	7	A286	18	20	11	HSS	20	30	6	Ti 6/4	19

B2: Data Analysis: Analysis of Variance

Table XVII: Analysis of Variance Tables

General Linear Model: UTS (ksi), Yield (ksi), ... versus Plate, Pin, ...

Factor	Type	Levels	Values
Plate	fixed	3	Al 7050, Ph13-8mo, Ti 6/4
Pin	fixed	3	A286, HSS, Ti 6/4
Lubr.	fixed	2	N, Y
Hole Prep (reduced)	fixed	2	A, B

Analysis of Variance for UTS (ksi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Plate	2	69540	43110	21555	23.63	0.000
Pin	2	134639	81609	40805	44.73	0.000
Lubr.	1	2662	226	226	0.25	0.622
Hole Prep (reduced)	1	12	438	438	0.48	0.493
Plate*Pin	4	41366	35693	8923	9.78	0.000
Plate*Lubr.	2	1547	2684	1342	1.47	0.243
Plate*Hole Prep (reduced)	2	5	202	101	0.11	0.895
Pin*Hole Prep (reduced)	2	5651	7285	3643	3.99	0.027
Lubr.*Hole Prep (reduced)	1	2402	2402	2402	2.63	0.113
Error	36	32843	32843	912		
Total	53	290667				

S = 30.2044   R-Sq = 88.70%   R-Sq(adj) = 83.37%

Analysis of Variance for Yield (ksi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Plate	2	76951	51587	25794	29.81	0.000
Pin	2	72307	43754	21877	25.28	0.000
Lubr.	1	2235	159	159	0.18	0.670
Hole Prep (reduced)	1	20	60	60	0.07	0.794
Plate*Pin	4	28801	25108	6277	7.25	0.000
Plate*Lubr.	2	1572	2844	1422	1.64	0.208
Plate*Hole Prep (reduced)	2	430	135	67	0.08	0.925
Pin*Hole Prep (reduced)	2	4748	6182	3091	3.57	0.038
Lubr.*Hole Prep (reduced)	1	2889	2889	2889	3.34	0.076
Error	36	31149	31149	865		
Total	53	221102				

S = 29.4149   R-Sq = 85.91%   R-Sq(adj) = 79.26%

Analysis of Variance for Stiffness (ksi), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Plate	2	824149	614654	307327	61.65	0.000
Pin	2	330258	192812	96406	19.34	0.000
Lubr.	1	20898	7043	7043	1.41	0.242
Hole Prep (reduced)	1	2497	2267	2267	0.45	0.504
Plate*Pin	4	27939	25244	6311	1.27	0.301
Plate*Lubr.	2	264	1041	521	0.10	0.901
Plate*Hole Prep (reduced)	2	5778	3669	1835	0.37	0.695
Pin*Hole Prep (reduced)	2	10554	11379	5689	1.14	0.331
Lubr.*Hole Prep (reduced)	1	13507	13507	13507	2.71	0.108
Error	36	179463	179463	4985		
Total	53	1415307				

S = 70.6052   R-Sq = 87.32%   R-Sq(adj) = 81.33%

B3: Data Analysis: Plots

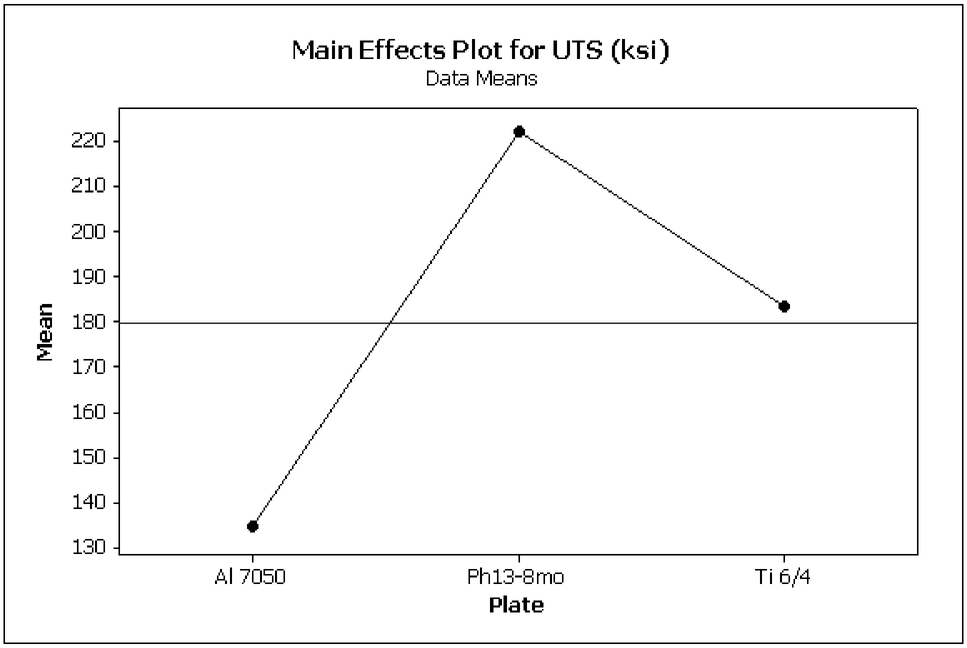

Figure 23: Plate main effects plot for bearing strength.

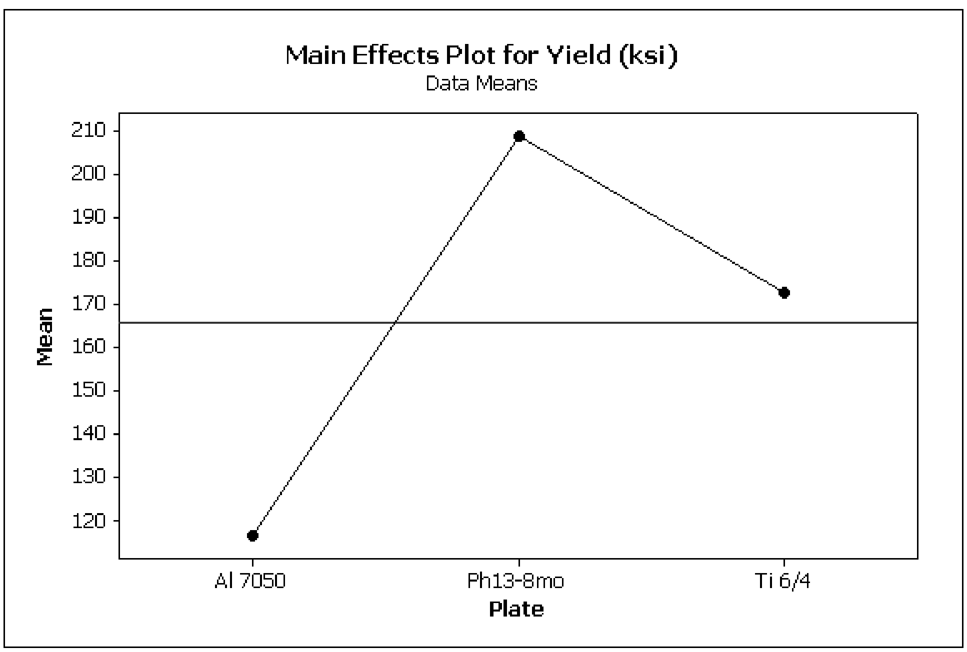

Figure 24: Plate main effects plot for bearing yield strength.

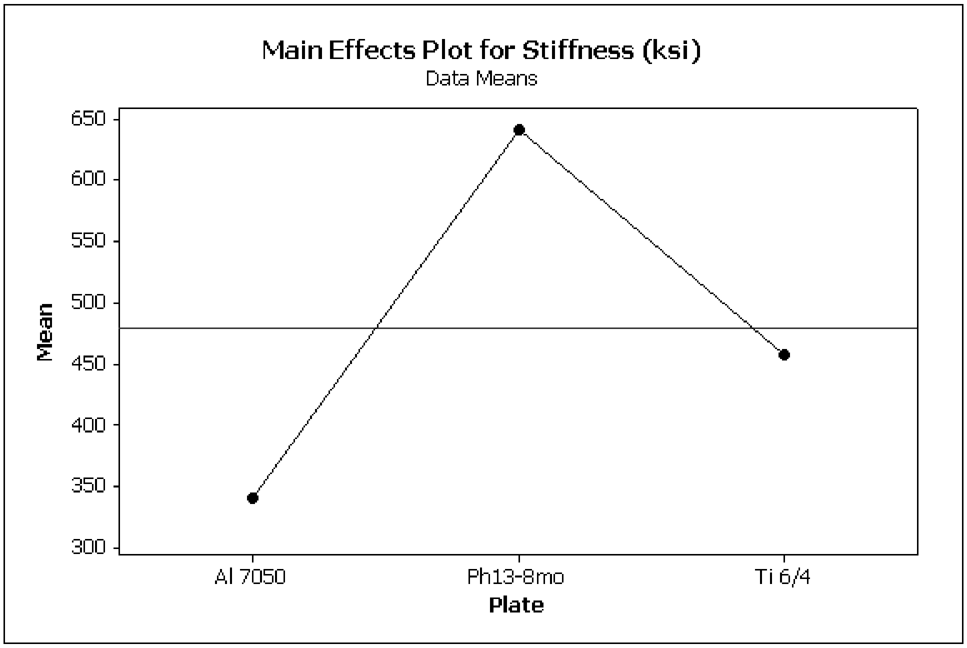

Figure 25: Plate main effects plot for bearing stiffness.

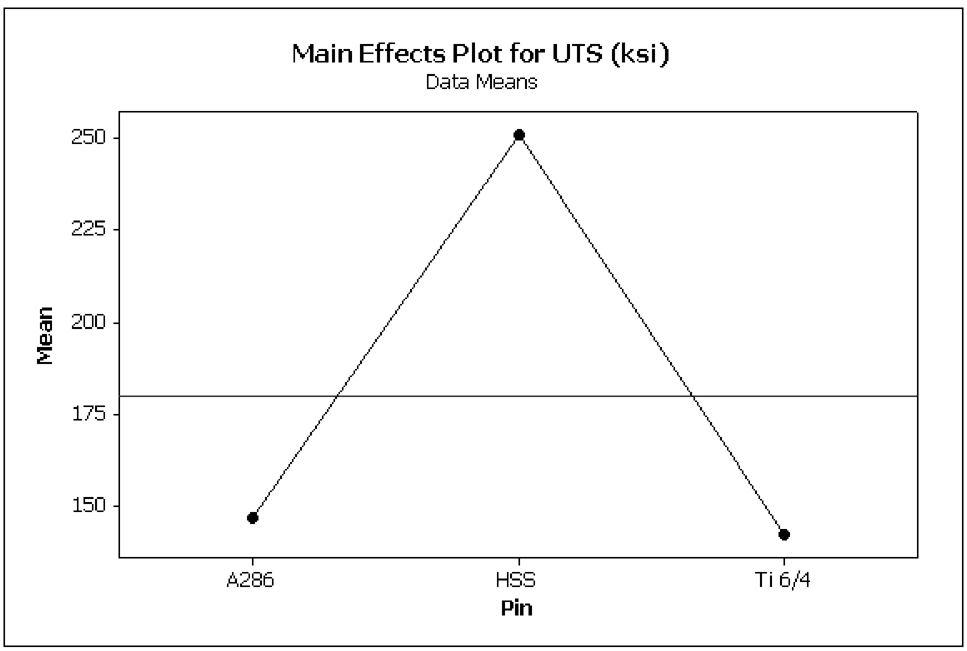

Figure 26: Pin main effects plot for bearing strength.

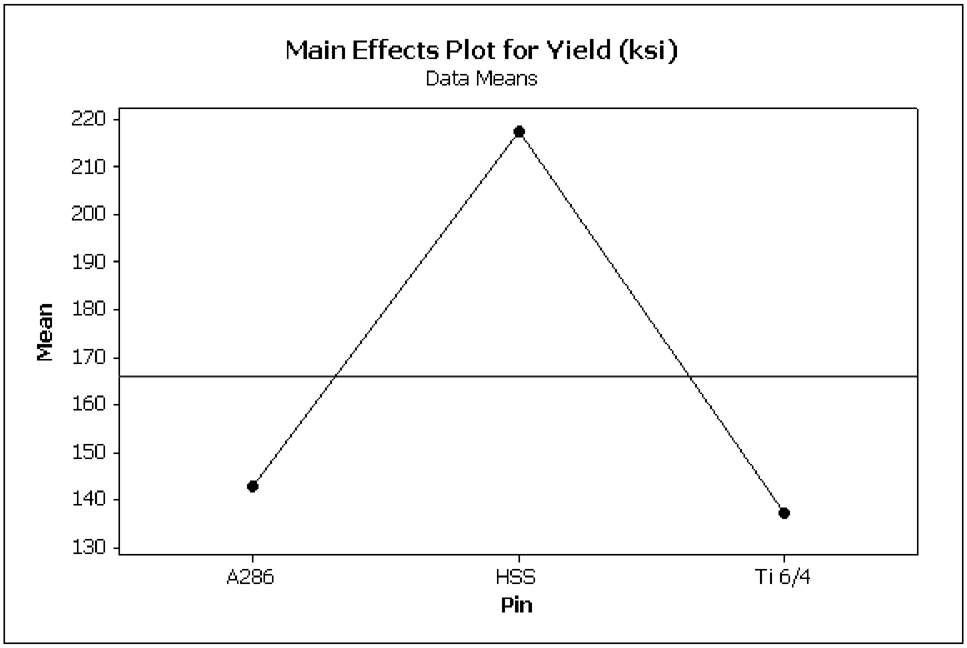

Figure 27: Pin main effects plot for bearing yield strength.

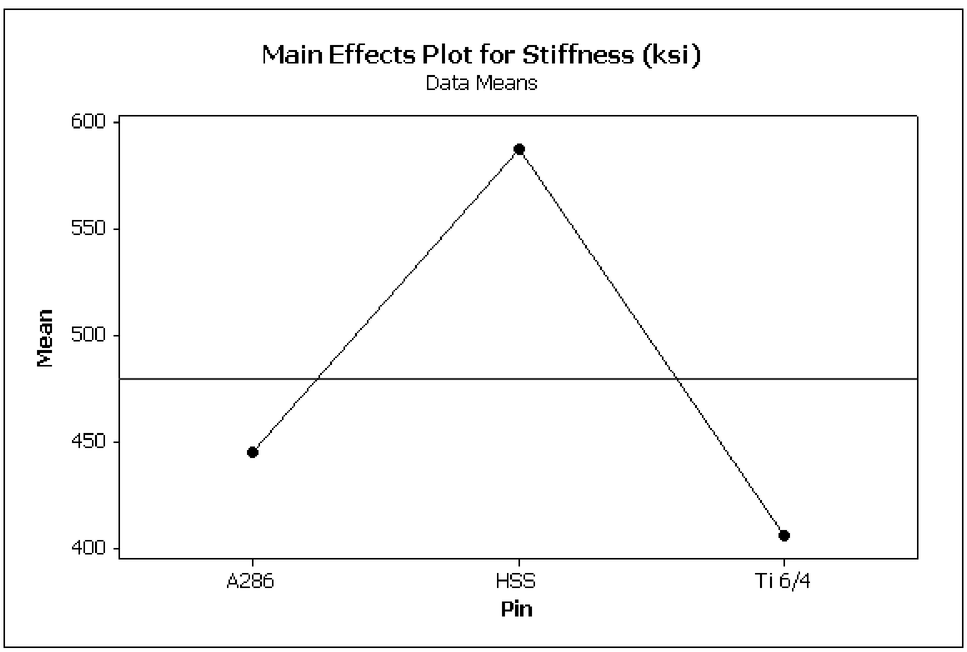

Figure 28: Pin main effects plot for bearing stiffness.

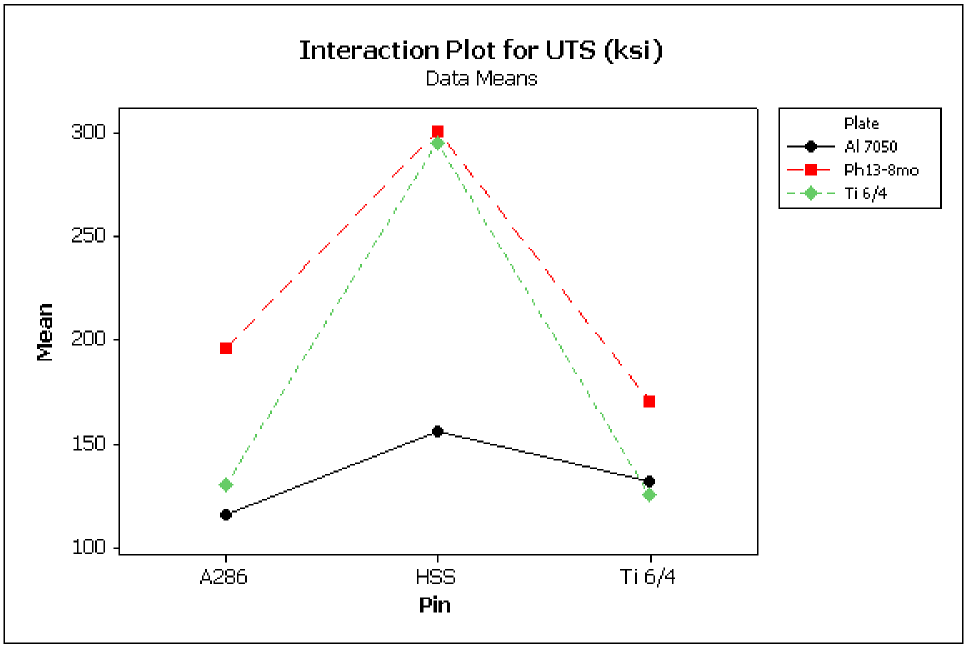

Figure 29: Plate x Pin interaction plot for bearing strength.

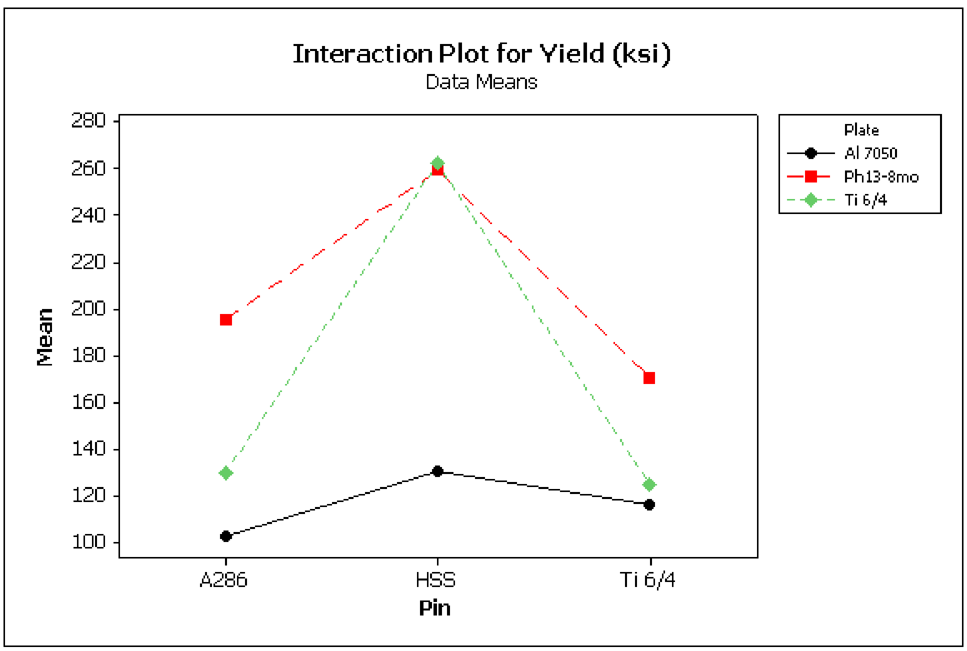

Figure 30: Plate x Pin interaction plot for bearing yield strength.

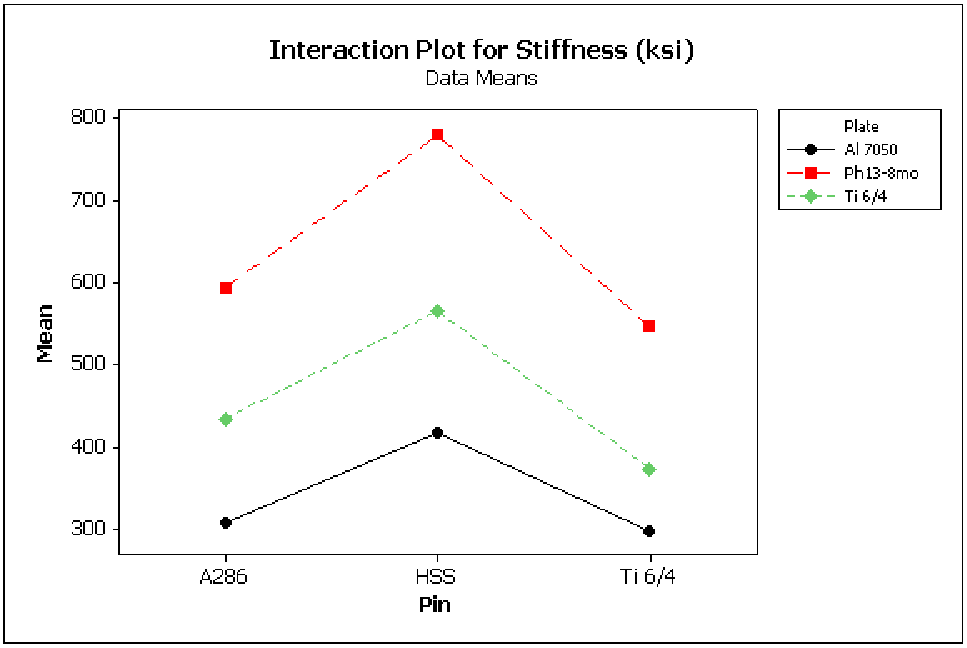

Figure 31: Plate x Pin interaction plot for bearing stiffness.

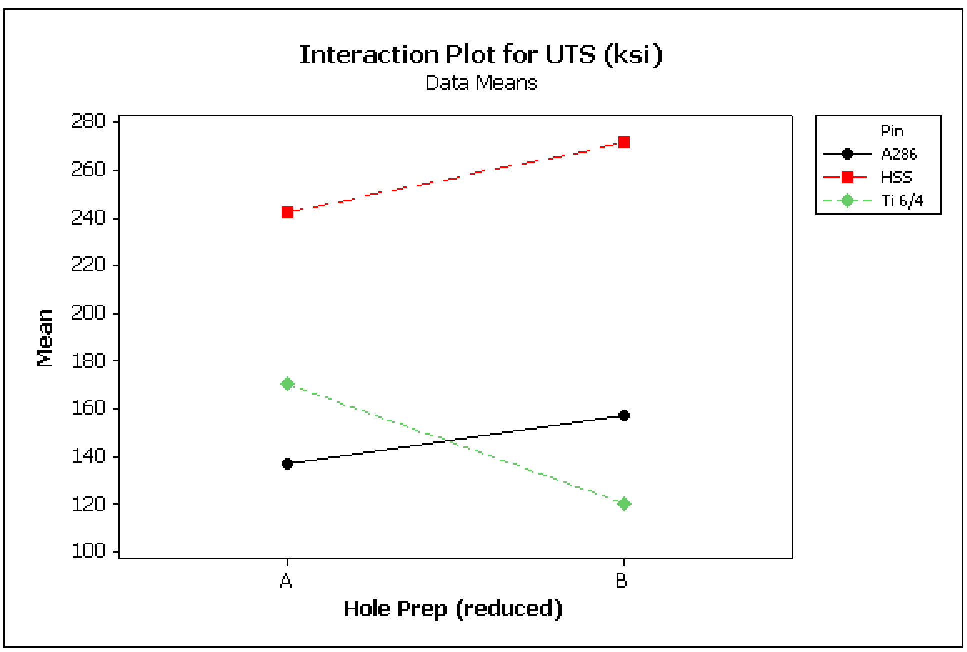

Figure 32: Pin x Hole Preparation Method interaction plot for bearing strength.

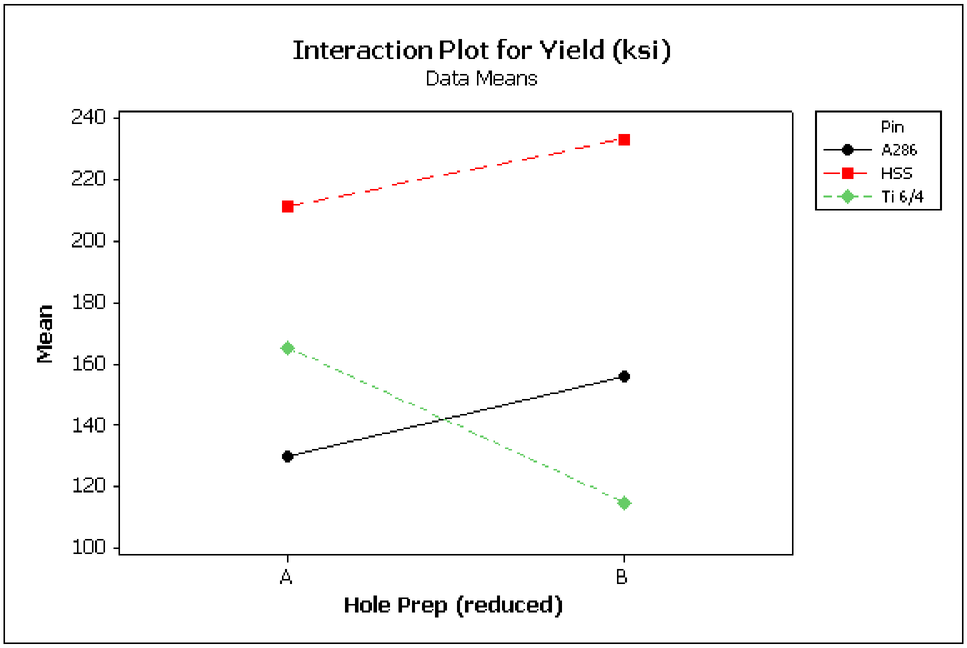

Figure 33: Pin x Hole Preparation Method interaction plot for bearing strength.

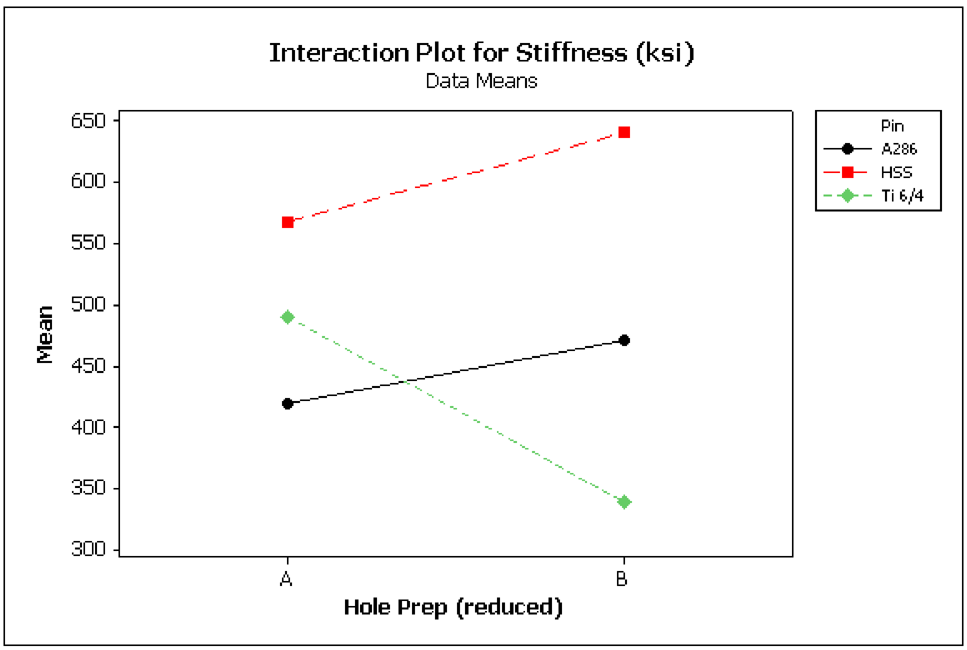

Figure 34: Pin x Hole Preparation Method interaction plot for bearing strength.